THE UNIVERSITY OF ALBERTA

THE URBAN HEAT ISLAND AND AIR POLLUTION WITH APPLICATION TO EDMONTON, ALBERTA

by

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled The Urban Heat Island and Air Pollution with Application to Edmonton, Alberta, submitted by Per Anders Daniels in partial fulfilment of the requirements for the degree of Master of Science.

13th August 1965
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ABSTRACT

Climatological investigations on air pollution in growing industrial cities are of great importance towards the prevention of losses in the economy and health of the city dwellers. This thesis deals with city climate, of which air pollution is an important characteristic, with particular reference to Edmonton, Alberta.

During the first half of 1964 a series of temperature traverses were conducted throughout the city. A significant temperature increase was found only at the city's built-up area and at the borders of the central business district. Over the residential areas there was a slow increase towards the city center. In the river valley the coldest part was found half way down the valley. This is explained by a drainage of cold air at the sides of the valley and warmer air over the middle of the river heated by the water. Isotherm maps are given for some of the traverses.

By means of the heat island model theory - which assumes the air over the city to be mixed up to a certain height called the mixing height - the maximum mixing height was calculated for the traverses. Conclusions are drawn about the height and its variation.

The conclusions from the traverses about the horizontal temperature distribution in connection with the heat island theory gave the result that the heat island - the pillow of warm air over the city - can be approximated by the shape of half an ellipsoid. From this conclusion an expression for computing the heat required to maintain the heat island was developed.

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By means of this expression the energy required to maintain the heat island, as found during the traverses, was calculated and compared to the amount of energy released by burning of fuels in the city and the amount of solar energy available. Regression analysis showed that the size of the heat island is strongest correlated with the cloud cover, less with air pollution and least with the fuel consumption and the solar radiation.

The second part considers air pollution and its connection with city climate. The nature of it, the damage it does, and ways of measuring it are described. The variation of the pollution concentration in the city is dealt with in connection with time of day, time of year, wind speed, wind direction, and macro-climatic conditions.

A number of actual observations have indicated that the pollutants are, on the average, uniformly distributed vertically throughout the heat island. This has been used to modify Sutton's equation for the calculation of the pollution concentration at a given location downwind from a point source. This modified equation has been extended to account for the pollution concentration at a given location from a point source upwind, assuming the wind direction is uniformly distributed within each major compass sector. Using this new equation again plus the information from a source survey of the city, the concentration at City Hall, Edmonton, was calculated for each direction with meteorological data from eight winter months for the early morning and late afternoon periods. The results of these calculations definitely support the theory of uniform mixing of pollutants with height within the heat island.

An extension of the measured values for the two periods for which information on the vertical temperature are available has been done in order to account for the concentration in the downtown area of the city during the whole day.

Assuming that the time periods used were representative for the whole day, the results showed that any polluting industries should definitely be restricted to the northern section of the downtown area in Edmonton.

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INTRODUCTION

The Value of City Climatological Investigations

The importance of climate in the planning of health resorts is obvious and several works,[1] mainly in Germany, have dealt with this aspect. The planner considering other types of city life also concerns himself with climate. Some of the problems from this point of view are: (a) location of recreational areas to get the maximum use out of them; (b) location of downtown areas to avoid sultriness; (c) use of the knowledge of the effect of urbanization of low lying areas on climate; (d) location of an airport to avoid high fog frequency. Theory and actual measurement of the city climate will often give valuable answers to problems such as these.

However, one of the most important problems for the planner to consider is air pollution, as air pollution produces economic problems and is harmful to the citizens' health in many industrial centers. These problems can partly be reduced by careful planning from the air pollution point of view. There are several estimates of the cost of the economic damage caused by air pollution. Munn[2] has suggested that it amounts to

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[1]For instance: H. Zenker, "Die Bedeutung des Lokalklimas für Kuranlagen - am Beispiel einer Tuberkulose - Heilstätte," Zeits.f.Met., Band 13, Heft 1-6, 1959, pp. 11-14; L. Trauner, "Klimakurort - Kurortklima," Zeits.f.Met., Band 13, Heft 1-6, 1959, pp. 17-21; G. Hentschel, "Untersuchungsergebnisse der Sterblichkeit unter verschiedenen lokalen Gegebenheiten," Zeits.f.Met., Band 13, Heft 1-6, 1959, pp. 33-44.

[2]R.E. Munn, "The Interpretation of Air Pollution Data, with Examples from Vancouver," Canada, Dept. of Transport, Met. Branch, Technical Circular Series, CIR-3454, TEC-351, 1961, p. 1.

42 dollars per person per year for the United States. Even though the per capita pollution damage in Edmonton is less than that of the average U.S. figure the damage may run into millions of dollars per year in the city.

One rather common method used in an effort to avoid high concentration of pollutants involves finding the direction from which the winds are least frequent and to locate new industries in the outskirts of the city in this direction. Another way is to locate green zones between the factories and the city, a technique that has been used in Russia where in some cities industry is segregated from the main settlement.[3] But there is more to the problem than finding the least frequent wind direction or locating green zones; the size of the heat island - the pillow of warm air over a city created by the city itself - is probably of greater importance. Summers[4] was the first to bring together the ideas from the problems of air pollution and the heat island effect. One of the important tasks of the city climatologist would therefore be to determine the size of the heat island, its variation in time, its connection with different weather situations, and the diffusion of pollutants within it.

It is desirable to conduct climatological investigations for large and growing industrial cities, so that they can be planned to prevent enormous loss to the economy and health of the citizens from air pollution.

The Purpose of This Study

There are three main purposes of this study, which investigates:

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[3] F. Kahn, Das Leben des Menschen, Stuttgart, 1921.

[4] P.W. Summers, "An Urban Heat Island Model; Its Role in Air Pollution Problems, with Applications to Montreal." A paper presented at the First Canadian Conference on Micrometeorology in Toronto, 1965, p. 18.

42 dollars per person per year for the United States. For Edmonton, with its population of approximately 357,000, the cost, then, accepting this estimate is about 15 million dollars per year.

One rather common method used in an effort to avoid high concentration of pollutants involves finding the direction from which the winds are least frequent and to locate new industries in the outskirts of the city in this direction. Another way is to locate green zones between the factories and the city, a technique that has been used in Russia where in some cities industry is segregated from the main settlement.[3] But there is more to the problem than finding the least frequent wind direction or locating green zones; the size of the heat island - the pillow of warm air over a city created by the city itself - is probably of greater importance. Summers[4] was the first to bring together the ideas from the problems of air pollution and the heat island effect. One of the important tasks of the city climatologist would therefore be to determine the size of the heat island, its variation in time, its connection with different weather situations, and the diffusion of pollutants within it.

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(1) the horizontal and vertical temperature distribution over the city of Edmonton. It sets out:

(a) to find pertinent temperature patterns within the city, and

(b) the size and variation of the heat island;

(2) the factors causing the heat island and its temporal and spatial variation over the city;

(3) the influence of the heat island on the dispersion of pollutants.

Proposed Method of Study

In order to find significant features of the horizontal temperature distribution over Edmonton it was necessary to undertake actual temperature measurements since no useful ones existed. In view of limited financial resources and the necessity for each recording to be made within a short period of time, the method of temperature traverses was deemed the most suitable for the purpose. A temperature traverse is a series of temperature measurements taken along a pre-determined route. The data were then to be analyzed by statistical methods in order to find significant features of the horizontal temperature distribution over the city.

To attempt to find significant features of the vertical temperature distribution a helicopter was used. However, instrumental failures made this part of the study fruitless. It was therefore necessary to use the records from the two daily radiosonde ascents to get the appropriate information. This information was to be combined with existing theories about the vertical temperature distribution over an urban area.

The agents causing the heat island over the city were to be analyzed by mathematical methods.

The connection between the heat island over a city and the diffusion of air pollutants from individual sources first had to be dealt with theo-

retically as no mathematical models existed that could be used for this purpose. The results from the theoretical study were then to be tested by means of pollution and climatological data about the city.

CHAPTER I

THE LOCATION AND PHYSIOGRAPHY OF THE EDMONTON REGION

Edmonton (population 357,000 in 1964), the capital of the province of Alberta, Canada, is located in the central part of the province at 53'35" North, 113'30" West 660 m (2200 ft) above sea level. The Edmonton area[1] was glaciated during the Wisconsin time by a continental glacier with a maximum thickness of approximately 1.6 km (1 mile). The retreat of the glacier from the area was largely by stagnation. The natural drainage of central Alberta is northeasterly and as the glacier retreated in that same direction, meltwaters impounded in front of the glacier producing marginal lakes. One such lake was Lake Edmonton which, when drained by the North Saskatchewan River, left a large area with flat lacustrine deposits on which the city is located. The even surface of the city's area is interrupted solely by the steep slopes of the North Saskatchewan River valley. The river enters the city in the southwest and leaves it after passing through diagonally. Within the city the valley seldom exceeds 1.6 km (1 mi) in width, and on the average the walls are 60 m (200 ft) high which in places form steep cliffs.

There are serveral open spaces, such as parks, playgrounds, sports fields, ravines, and an airport within the city's roughly 150 km^2

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[1]The description in this paragraph is mainly taken from: L.A. Bayrock and G.M. Hughes, "Surficial Geology of the Edmonton District, Alberta," Preliminary Report, Research Council of Alberta, Edmonton, 1962.

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($60\ mi^2$) built-up area. The largest of these are shown in Fig. 1 which is a land use map for the city of Edmonton. The residential areas, as marked on Fig. 1, are generally built up with one-and two-story houses which are rather close to one another. In the city's commercial areas (Fig. 1) the houses are closer and generally higher. Although there are many small areas within the city classified as commercial areas, there are, with the exception of the city core, only three larger agglomerations of commercial activity: one around 82nd Avenue and 104th Street, one in Jasper Place and one just north of the city core. These three areas are marked in Fig. 1. The city core, also referred to as the Central Business District, has the highest and the largest buildings. However, the size of the buildings here varies a great deal, ranging from small two-story buildings to a few buildings of about ten stories. Parts of the river valley, especially east of the Low Level Bridge, are built up residentially. In the countryside around the city there are clusters of houses and single farms. There are few trees in these areas and the vegetation generally consists of grasses and low bushes. There are no large permanent water bodies in the vicinity of the city other than the North Saskatchewan River.

Fig. 1 shows locations within the city and a circle with a radius of 6400 m (4 mi) on which computations in this study are based. The circle limits the area which will later[2] be taken as the city's built-up area.

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[2] See page 63.

Legend: AB - Prov. Govt. Administration Building
CH - City Hall
CP - City Power Plant
HLB - High Level Bridge
105 B - 105th St. Bridge
LLB - Low Level Bridge
U of A - University of Alberta

Fig. 1. The city of Edmonton, Alberta. The river valley and the main ravines within the city are indicated by a thick line. The circle encloses the area which later will be taken as the total area of the built-up area of the city. Classification of the city area is made by the City Planning Office, Edmonton.

CHAPTER II

CLASSIFICATION OF THE THESIS AND DEFINITION OF CLIMATOLOGICAL SUBDIVISIONS

This study deals mainly with the horizontal and vertical temperature distribution over a city - Edmonton, Alberta - its air pollution and the connection between the three dimensional temperature distribution and the dispersion of air pollution over the city. It can therefore best be classified as a study in urban climatology. Kratzer[1] gives three definitions of this concept[2]:

> Man könnte darunter die Einwirkungen des Grossraumklimas auf die Stadt verstehen, wie sie z.B. in den Tropen oder in den Trockengebieten gebaut wurde oder in den gemässigten Zonen in die Polargebieten. Je nachdem hat die Stadt vom Klima her ein anderes Gesicht. Oder wir verstehen darunter einfach das der Stadt eigentümliche Klima, wodurch es sich von seiner Umgebung unterscheidet, welche klimatischen Eigentümlichkeiten sie hat, woher diese kommen, welche Ursachen sie haben. Schlieslich könnte man darunter verstehen die Wirkungen und Folgen dieses Klimas auf den Städter und seine Gesundheit.

Although closely related to meteorology the study of urban climate

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[1]A. Kratzer, <u>Das Stadtklima</u>, Braunschweig, 1956, p. 1.

[2]Translated: With it one can understand the influences of the large scale climate on the city, as it for instance should develop in the hot tropical zones, in the temperate zones, or in the polar zones. Accordingly, the city has a different visage from the climate point of view. Or we understand simply the specific climate of the city, whereby it differs from its surroundings, what climatic characteristics it has, why and how these occur. Finally, one can understand with it the influences and consequences of the climate on the city dwellers and their health.

is classified as climatology. Climatology is generally divided into three subdivisions: macro-, meso-, and micro-climatology. The subdivisions are best distinguished by the space in which they operate.[3] In macro-climatic space, the spatial and temporal distributions of meteorological elements over a large area are uniform, determined by the large scale atmospheric circulations, latitude, sea or land location, and the height above sea level. Meso-climatic space, the spatial and temporal distributions of meteorological elements are determined by local factors such as topography, direction and exposure of slopes, ground cover (vegetation, buildings, etc.), and the nature of the ground. Micro-climatic space deals with the spatial and temporal distributions of meteorological elements determined by factors operating only in small areas close to the energy changing surfaces. The most important energy changes are those associated with heat exchange, with changes of water state, and with wind-ground friction. The main energy changing surface is the ground surface, inclusive of vegetation cover and buildings.

Flohn[4] gives the spatial limits that can be applied to the definitions above:

macro-climate: from 10^4 m and upwards

meso-climate: from 10^0 to 10^4 m

micro-climate: from 10^{-2} to 10^0 m

The space in which this study is undertaken - the city of Edmonton - is

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[3]W. Böer, "Zum Begriff des Lokalklimas," Zeits.f.Met., Band 13, Heft 1-6, 1959.

[4]H. Flohn, "Grundsätzliche Probleme der Wettervorhersage," Veröffentlichungen des Instituts für Meteorologie und Geophysik der freien Universität Berlin, Band 11, Heft 3, 1954.

within the meso-climatic space. There are of course also interrelationships with factors operating in the two other spaces. For instance, the cloud cover in the macro-climatic space influences temperature in the meso- and micro-climatic spaces. Conversely the cloud cover is made up of particles which have risen from the areas of meso- and micro-climatic spaces.

This thesis is thus best classified as a study in urban or meso-climatology.

CHAPTER III

THE MACRO- AND, FOR THE TRAVERSES, THE MESO-CLIMATE OF THE AREA STUDIED

A. The Macro-climate of Central Alberta

1. Weather System Affecting the Area[1]

Winter. The macro-climate of central Alberta in wintertime is largely determined by two large quasi-stationary anti-cyclonic systems, a cold one over northwestern Canada, and the other a warm one over the western United States. Between these two highs, there is a well-marked col in which central Alberta is located.

The principal associated air masses affecting central Alberta are:

(a) Continental arctic air. Its origin is over the snow and ice-covered surfaces of continental Canada and Alaska. The temperatures here are very low.

(b) Maritime polar air. Its origin is over the relatively warm waters of the central Pacific Ocean. These modified warm westerly and southwesterly winds, "the chinook," move in aloft causing extreme inversions and when occasionally they reach the ground give a welcome relief between the cold spells. However, the air reaches Edmonton in wintertime only infrequently and for short periods.

Along the frontal zones between the air masses, cyclonic activity frequently develops in central Alberta, moving southeastwards and eastwards into Saskatchewan, and plays an important role in the weather

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[1]Part of this discussion in this section is taken from: W.G. Kendrew and B.W. Currie, The Climate of Canada, Ottawa, 1955.

of the province, especially in relation to precipitation.

Summer. In view of the heating of the continent there is a marked disappearance of the anti-cyclones in summer. On the other hand there is an intense subtropical high pressure system centered in the North Pacific Ocean. Because of this high pressure, the winds along the B.C. coast are generally northerly. Thus the flow of air over the Rocky Mountains is limited. For central Alberta this implies that the flow of air generally is northwestern or southeastern. However, the winds are more variable than during the winter.

With northwesterly winds arctic air is brought in from the partially frozen land and waters of northwestern Canada. This air, heated in the lower layers during its passage southeastwards over the country, develops steep lapse rates and shower activity is common. This air is the most frequent one over the area. With southeasterly winds, warm and moist modified polar continental air is brought in from the Great Plains area. This air gives the area most of its precipitation.

2. The Climate of the Edmonton Area from Long Term Records

Table 1 gives the long term records from the Industrial Airport. This table as well as the following description[2] was by the Dominion Public Weather Office, Edmonton, Alberta.

> Edmonton, at 53'35"N, is the most northerly city of its size in Canada. Its protected position in the lee of the Rocky Mountains gives an annual precipitation of only 18 inches. However 64 per cent of this falls during the growing season of spring and summer, and this supplies sufficient moisture for successful farming.
>
> The climate is described as a cold temperate climate, but is not so severe as might be expected in a continental climate at 53°N. The chinooks, which modify the long win-

---

[2]Dominion Public Weather Office, "Meterological Summary 1963, Long Term Records 1881-1963,' Edmonton, Alberta," Edmonton, 1963, p.1.

TABLE 1 - ANNUAL METEOROLOGICAL SUMMARY - EDMONTON, ALBERTA
COMPARATIVE RECORDS

Monthly and annual averages and extremes for the total period observations have been taken (1881 - 1963)

T E M P E R A T U R E S

Month	Mean Maximum	Mean Minimum	Mean Monthly	Absolute Maximum	Year	Absolute Minimum	Year	Highest Monthly Mean	Year	Lowest Monthly Mean	Year	Degree Days (normal)	Mean Relative Humidity
Jan.	15.2	-2.0	6.6	56.5	1889	-57.0	1886	22.3	1931	-18.0	1950	1780	82
Feb.	20.3	2.0	11.2	62.0	1889	-57.0	1893	31.7	1931	-17.0	1936	1520	81
Mar.	31.0	13.2	22.1	72.0	1889	-39.5	1888	36.6	1910	8.5	1899	1290	76
Apr.	50.0	28.9	39.5	87.7	1939	-15.0	1920*	48.8	1906	26.8	1954	760	61
May	63.6	40.5	52.1	94.0	1936	10.1	1942	57.3	1936*	43.6	1907	410	57
June	68.5	47.0	57.8	99.0	1937	25.0	1887*	65.7	1961	52.4	1902	220	64
July	74.4	51.7	63.1	98.0	1924	29.0	1918	66.4	1960*	55.4	1881	90	67
Aug.	71.3	48.6	60.0	96.0	1933	26.0	1887	65.8	1961	55.9	1907	180	69
Sep.	62.6	40.4	51.5	88.3	1950	11.0	1951	59.8	1938	41.7	1926	440	70
Oct.	51.6	30.7	41.2	83.1	1945	-15.0	1919	48.1	1915	29.1	1919	750	68
Nov.	32.2	16.8	24.5	74.0	1931*	-44.0	1883	39.5	1917	-0.4	1896	1220	77
Dec.	21.0	5.5	13.3	61.4	1939	-55.2	1938	26.8	1959	-9.7	1933	1660	82
	46.8	26.9	36.9	99.0	1937	-57.0	1886 1893	66.4	1906 1960	-18.0	1950	10320	71
N#	30	30	30					82		82		30	20

P R E C I P I T A T I O N — WIND — SUNSHINE

Month	Rain (mean)	Newly fallen snow (mean)	Total Preciptn. (mean).	Greatest Monthly Precpt.	Year	Least Monthly Precpt.	Year	Greatest Monthly Snowfall	Year	Speed m.ph. (Mean)	Prevailing direction by hours	Total hrs. sunshine (Mean)
Jan.	0.01	9.4	0.95	2.50	1935	T	1931	25.0	1935	7.8	S	85.9
Feb.	0.01	7.6	0.77	2.31	1939	T	1931	22.9	1939	8.0	S	116.1
Mar.	0.05	7.8	0.83	2.76	1940	0.10	1915	27.6	1940	8.9	S	165.7
Apr.	0.50	6.0	1.10	3.47	1955	0.01	1905	29.0	1955	10.4	S	221.3
May	1.71	1.2	1.83	7.67	1902	0.20	1898	9.9	1918	10.5	N W	266.9
June	3.15	0.0	3.15	8.53	1914	0.45	1949	0.2	1922	9.9	NW	253.4
July	3.34	0.0	3.34	11.13	1901	1.28	1939	0.0	----	8.8	NW	309.2
Aug.	2.55	0.0	2.55	6.43	1899	0.03	1939	1.0	1900	8.3	NW	269.6
Sep.	1.26	0.9	1.35	4.32	1901	0.06	1909	11.2	1926	9.0	S	188.7
Oct.	0.49	4.1	0.90	2.28	1919	0.06	1895	18.1	1919	8.9	S	156.9
Nov.	0.14	7.4	0.88	3.57	1906	0.01	1928	35.5	1906	8.2	S	101.5
Dec.	0.05	9.4	0.99	2.85	1933	0.07	1905	28.5	1933	7.6	S	77.8
	13.26	53.8	1864	11.13	1901	T	1931	35.5	1906	8.9	S	2213.0
N	30	30	30	69		69		69		25	25	44

* More than one year with the latest shown

\# Number of years of observation

Source: Dominion Public Weather Office, Edmonton, Alberta, "Meteorological Summary 1963, Long term records, 1881-1963, Edmonton, Alberta." Edmonton, 1963.

ter just east of the Rockies do not usually reach as far east as Edmonton. However, their modifying influence does extend to Edmonton for brief spells nearly every winter. The frequency of the chinook is variable. Some winters will be quite mild with recurring chinooks. Other winters may witness only one. Average winter temperature is 13.7°F. Low temperatures of -30°F occur on the average three or four times each winter. Extremely low temperatures of -40°F or less occur about once every three winters.

Depth of snow on the ground averages 7 inches by midwinter and seldom exceeds 14 inches in the City area.

Average annual wind speed of 8.9 miles per hour is among the lower reported on the prairies.

Summers in Edmonton are usually pleasant. Moist, tropical Gulf air, which brings heat waves to most of the interior of the continent, never reaches Edmonton. Maritime Pacific air, which comes from the west, is dried by the passage over the Rockies. Consequently, relative humidity averages are lower here than elsewhere on the western plains. Highest temperature ever recorded in Edmonton is 99°F and seldom does the temperature exceed 90°F. Average July maximum temperature is only 74°F.

Edmonton's altitude is 2200 ft, which contributes to its cool summer nights. Average July minimum is 52°F.

B. The Meso-climate of Edmonton During the Occasions Studied Compared with Average Conditions

During January, February and March, 1964, 31 temperature traverses were undertaken throughout Edmonton in order to get a picture of the horizontal temperature distribution over the city. These traverses, in this section only, will be referred to as "winter traverses," and the period January, February and March as "winter." During June and July, 1964, 11 similar traverses were made. These traverses, in this section only, will be referred to as "summer traverses," and the period June and July as "summer." Before generalizations of the results from the traverses can be made, it is necessary to investigate to what extent the weather conditions, the air pollution situation and the time of day of the traverses are representative of average conditions. The horizontal temperature distribution is caused by the combination of several

factors, the most important of which will be discussed singly. The time used throughout the thesis is local time: Mountain Standard Time.

Time of day. According to Kratzer[3] there is a definite diurnal variation of the difference in temperature between an urban area and the surrounding countryside. The maximum difference occurs at night and the minimum at noon. To ensure that there would be a measureable difference in temperature, most traverses in both winter and summer were done during early evenings, nights and early mornings, as can be seen from Table 2.

TABLE 2 - THE NUMBER OF TRAVERSES UNDERTAKEN DURING DIFFERENT TIMES OF THE DAY IN 1964

	Time of Day (MST)					
	0000-0359	0400-0759	0800-1159	1200-1559	1600-1959	2000-2359
Winter	9	10	1	2	7	2
Summer	5	3	0	1	0	2

The conclusions from the traverses are assumed to be valid only for times from about 1600 to 0700 hrs in wintertime and 2000 to 0700 in summertime.

Time of the year. Kratzer[4] states that the annual variation in the increase of the temperature of the urban area over the surroundings is small, but that there is a slight fall maximum and a spring minimum.

Air pollution. The amount of pollution in the air is significant in causing a temperature difference between the city and the country. Since 1960 there has been a sampler (A.I.S.I.) for particulate

[3] A. Kratzer, Das Stadtklima, Braunschweig, 1956, p. 62.

[4] Ibid., p. 60.

matter installed in Edmonton. A measured concentration, expressed as a "soiling index," (see page 94) is taken every second hour and represents the total amount of particulate matter that entered the sampler during a two-hour period. This soiling index in wintertime showed a definite diurnal variation. It is therefore necessary to account for the diurnal variations when comparing the air pollution concentration during the winter traverses with average winter concentration. The data available were:

(a) Monthly average soiling index for the three years, 1960, 1962 and 1963.

(b) The number of two-hour periods with soiling index larger than 0.9 by season for 1963. This figure, 0.9, has been selected by the Department of Health for presenting data on air pollution in Edmonton. Hereafter, a two-hour period with a soiling index larger than 0.9 will be referred to as a "polluted period."

To get the mean concentration by four-hour periods of the day from this material during the winter the following method was used: First, calculation was made of the number of polluted periods by four-hour intervals of the day, and for the whole day. These figures are listed in Table 3 as "No. of polluted periods." Secondly, the number of polluted periods for each four-hour interval was expressed as a percentage of the total number of polluted periods for the whole day. These percentages are listed in Table 3 as "percentage of total figure." Thirdly, the mean of the monthly mean soiling index for a two-hour period for January, February and March during the years 1960, 1962 and 1963 was calculated. To get the daily mean soiling index for this period, this two-hourly value was multiplied by twelve. The daily variation of the total pollution was assumed to be represented by the

variation of the number of polluted periods. By utilizing the percentages for each four-hour interval in the second stage and the daily mean soiling index, it was possible to obtain the distribution of the daily soiling index by four-hour intervals for the day. To obtain the index for each two-hour period, the four-hourly figures were divided by two. These figures are in Table 3 listed as "two-hourly period mean soiling index." Fourthly, the mean of the mean soiling indexes during the traverses was calculated by four-hourly periods. These figures are listed in Table 3 as "mean traverse soiling index."

The following example clarifies the method: of all two-hour periods between 0000 and 0200 hrs during the winter 1963 two were "polluted," and for the period 0200 to 0400 hrs six were "polluted." Thus, for the first four-hour periods of the day there were eight polluted periods. The total number of polluted periods during the winter was 126. Of these, eight (or six per cent) occurred between 0000 and 0400 hrs. The mean soiling index per two-hour period was 0.55, or for the whole day 6.6. The index for the interval 0000 to 0400 hrs was six per cent of this figure, or 0.40. Thus, for each two-hour period during the first interval of the day the soiling index was half of this figure, or 0.20. The mean of the mean soiling index for the traverses undertaken between 0000 and 0400 hrs was 0.16.

For the summer traverses the corresponding division of the soiling index for the day was not necessary since the number of polluted periods showed much less variation during the day. The mean soiling index during the summer traverses was 0.19, while the period mean soiling index for June and July was 0.26.

The air pollution situation during the time of the summer

TABLE 3 - MEAN SOILING INDEX DURING THE WINTER TRAVERSES AND THE PERIOD MEAN SOILING INDEX FOR DIFFERENT PERIODS OF THE DAY

	Time of Day (MST)						
	0000-0359	0400-0759	0800-1159	1200-1559	1600-1959	2000-2359	Total
No. of polluted periods*	8	10	24	41	28	15	126
Percentage of total periods	6	8	19	33	22	12	100
Two-hourly mean soiling index*	.20	.26	.63	1.09	.73	.40	6.62
Mean traverse soiling index	.16	.26	.68	.23	.45	.33	4.22

*Source: D.T. Keenan, "Air Pollution in Edmonton 1963," Government of Alberta, Dept. of Health, 1964.

traverses was similar to the period mean. In winter, for traverses between 2000 and 1200 hrs the air pollution situation was similar to the period mean but for traverses between 1200 and 2000 hrs the air was less polluted.

Cloud cover. Table 4 gives the mean amount of cloud cover during the traverses for the time intervals for which period means are available. As can be seen in the table, the cloud cover during the traverses was less than the period means in both summer and winter for daily intervals with more than one traverse.

Wind speed. Edmonton's wind shows a maximum during a summer afternoon and a minimum at night, but in winter the diurnal variation is slight. However, these variations were not considered in the analysis. Table 5 gives the mean wind speed during the traverses and the period mean for summer and winter.

TABLE 4 - THE MEAN CLOUD COVER DURING THE TRAVERSES AND THE PERIOD MEAN CLOUD COVER DURING DIFFERENT TIMES OF DAY

	Time of Day (MST)				
	0130-0730	0730-1330	1330-1930	1930-0130	Total
No. of winter traverses	15	1	9	6	31
Mean cloud cover for winter trav.	4.0/10	9.9/10	4.2/10	4.2/10	4.5/10
Period mean cloud cover for winter*	6.3/10	7.3/10	6.8/10	5.8/10	6.3/10
No. of summer traverses	8	1	0	2	11
Mean cloud cover for summer trav.	1.9/10	1.8/10	-	7.3/10	2.9/10
Period mean cloud cover for summer*	6.4/10	6.4/10		5.6/10	6.5/10

*Source: W.G. Kendrew and B.W. Currie, The Climate of Central Canada, Ottawa, 1955, p. 143.

TABLE 5 - MEAN WIND SPEED DURING THE TRAVERSES AND THE PERIOD MEAN SPEED BY SEASON

	No. of observations	Mean wind speed (mi/h)
Winter, traverses	31	8.5
Winter, period mean*		8.2
Summer, traverses	11	7.0
Summer, period mean*		9.4

*Source: Dominion Public Weather Office, Edmonton, Alberta, "Meteorological Summary 1963, Long Term Records, 1881-1963, Edmonton, Alberta," Edmonton, 1963.

The wind speed was the same during the winter traverses as the period mean wind speed; while during the summer the mean wind speed during the traverses was somewhat less than the period mean speed.

Wind direction. The vertical temperature distribution generally

varies according to the wind direction. With northerly winds cold air is brought in over the relatively warmer ground making the vertical temperature distribution unstable. With southerly winds, relatively warm air moves in over the ground resulting in stable vertical temperature distribution. Therefore the frequency of the various wind directions during the traverses must be compared to the period mean frequency.

TABLE 6 - WIND DIRECTION BY PERCENTAGE FREQUENCY FOR THE TRAVERSES AND PERIOD MEANS

	Wind Direction								
	N	NE	E	SE	S	SW	W	NW	Calm
Winter, traverses	10	6	13	6	23	16	19	7	0
Winter, period mean*	8	7	12	8	23	15	13	13	1
Summer, traverses	0	18	9	18	18	36	0	0	0
Summer, period mean*	9	7	11	10	14	10	20	19	1

*Source: W.G. Kendrew and B.W. Currie, The Climate of Central Canada, Ottawa, 1955, p. 142.

The wind direction distribution during the traverses for the winter period agrees generally with the long term records. In summer southwest winds prevailed during too many occasions and too few traverses were made with westerly or northwesterly winds prevailing. However, these discrepancies were assumed to be fairly insignificant.

Precipitation. The monthly period mean precipitation (see Table 1) is 0.85 inches for the winter. For the winter traverses, traces of precipitation were reported at the Industrial Airport three times, and

[illegible]

[illegible]

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

[illegible]

on two other occasions 0.01 inch was reported. For the summer, the monthly period mean (see Table 1) is 3.25 inches, but during the traverses there was no precipitation, making the traverses not representative of situations with precipitation.

Snow Depth. The reports from the Industrial Airport[5] showed that the ground was covered with snow during all the winter traverses and that the mean snow depth was 2.6 inches. The snow cover during the winter traverses was assumed to be representative for mean conditions during the winter.

Vertical Temperature Distribution in Early Morning. The temperature difference between the city and the country depends (amongst other things) on the vertical temperature distribution in the lowest part of the atmosphere. There are two daily radiosonde ascents in Edmonton, one at 0500 hrs, the other at 1700 hrs. However, only the radiosonde data from the early morning (0500 hrs) are summarized. The vertical temperature data from this hour for days with a traverse in time nearer to 0500 hrs than to 1700 hrs were used in the comparison with the average vertical temperature condition. The number of occasions used were in winter twenty-one and in summer eight. Fig. 2 shows the cumulative frequency of early morning ground inversions by season for the years 1957 to 1960 and the cumulative frequency of inversions by season for days that could be used from the traverse point of view. The abscissa indicates the temperature increase from the ground up to 900 mb. The 900 mb surface is approximately 300 m (1000 ft) above Edmonton. For example, in 40 per cent of all winter mornings 1957 to 1960 there was an inversion of 4°C/300 m or more.

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[5] Dominion Public Weather Office, "Snow Depth at the Industrial Airport, Edmonton, for 1964," unpublished.

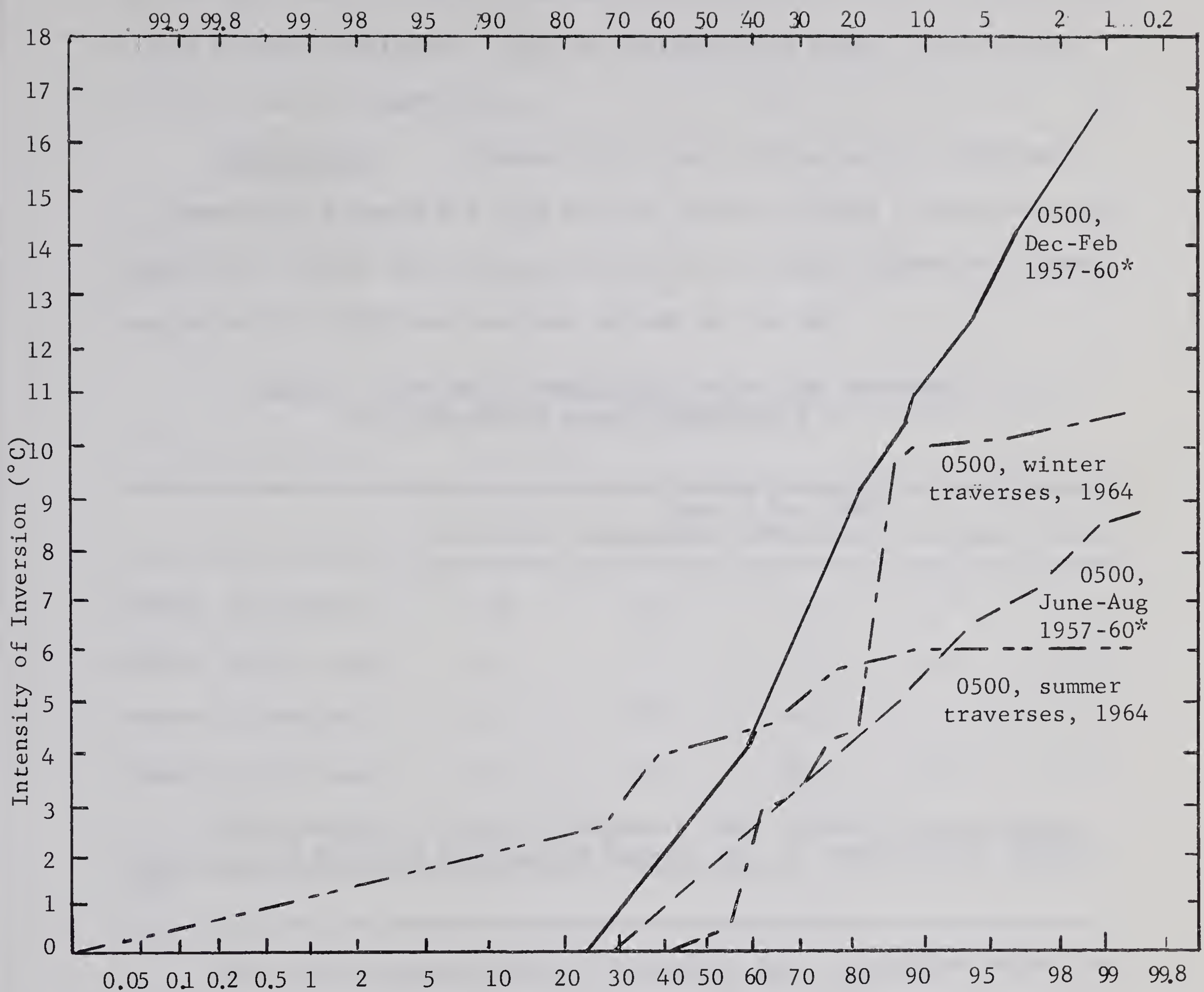

Fig. 2. Cumulative frequencies of inversions 0500 hrs at Edmonton.

*Source: R.E. Munn and J.H. Emslie, "The Frequency and Intensity of Early Morning Ground Inversions at Edmonton 1950-1960," Canada, Dept. of Transport, Met. Branch, Tec. Cir. Series 4009, Tec. 511, 1964.

The graph shows that for traverses in wintertime undertaken closer to 0500 hrs than to 1700 hrs the ground inversion was less developed than during average conditions. For the corresponding summer traverses the situation was the opposite.

Temperature. Temperature itself influences the difference in temperature between the city and the country. Table 7 gives the mean temperature during the traverses as well as the mean temperature during the period 1941-1950 for six-hour periods of the day.

TABLE 7 - THE MEAN TEMPERATURE DURING THE TRAVERSES AND THE PERIOD MEAN TEMPERATURE (°F)

	Time of Day (MST)				
	2030-0230	0230-0830	0830-1430	1430-2030	Total
Winter, traverses	8	6	-4	9	7
Winter, period mean*	12	9	16	18	13
Summer, traverses	42	43	46	-	43
Summer, period mean*	57	51	66	69	61

*Source:Canada, Dept. of Transport, Met. Branch, Climatological Summaries for Selected Stations in Canada, Vol. 1. Temperature. Toronto, 1959.

The table indicates that the traverses were undertaken during conditions colder than average.

Relative Humidity. The water content in the air is of importance for the temperature difference between the city and the country. Though not a measure of the absolute water content of the air, the relative humidity is connected to it. Table 8 gives for six-hour periods the mean relative humidity during the traverses as measured at the Industrial Airport and the period mean for 1941 to 1950 from the same location.

[illegible]

TABLE 8 - THE MEAN RELATIVE HUMIDITY DURING THE TRAVERSES AND THE PERIOD MEAN RELATIVE HUMIDITY

	Time of Day (MST)				
	2030-0230	0230-0830	0830-1430	1430-2030	Total
Winter, traverses	72	79	75	62	74
Winter, period mean*	84	87	77	73	80
Summer, traverses	53	70	63	-	61
Summer, period mean*	76	87	55	49	66

*Source: Canada, Dept. of Transport, Met.Branch, Climatological Summaries for Selected Stations in Canada. Vol. II. Humidity and Winds. Toronto, 1959.

The values in the table indicate that both summer and winter traverses were conducted during conditions with lower relative humidity than average.

Absolute Humidity. The absolute humidity during the traverses can be assumed to be less than average since both the temperature and the relative humidity were lower than the period mean ones.

The Total Insolation. The total insolation is of great importance for the development of the temperature difference between the city and the country. Total insolation has been measured at the Industrial Airport in Edmonton since 1960. In Table 9 the mean daily total insolation for the winter period is arrived at by averaging the monthly daily mean insolation weighted according to the number of traverses each winter month. This procedure was also used for the corresponding summer figure. The mean total insolation during the daily insolation periods preceding the traverses is also given in Table 9.

[illegible]

TABLE 9 - THE PERIOD MEAN TOTAL INSOLATION (1960-1964), AND THE MEAN TOTAL INSOLATION FOR THE TRAVERSES

	Total Insolation (ly) per day
Winter, traverses	259
Winter, period mean*	227
Summer, traverses	701
Summer, period mean*	550

*Source: Canada, Dept. of Transport, Met. Branch. Monthly Radiation Summaries. Vols. 1,2,3,6,7, Toronto, 1960-1964.

The total insolation in the daytime preceding the winter traverses was on the average somewhat larger than the period mean. For the summer traverses the insolation was larger still.

Conclusions

The results of this study are valid only for times between 1700 and 0800 hrs. The measured items for which the most important deviations from mean conditions occurred during the traverses were:

The cloud cover; less than the mean;

The air pollution concentration; 1200-2000 hrs in wintertime, less concentration, otherwise the same as the mean;

The precipitation: no precipitation;

The temperature: colder than the mean;

The absolute humididty: less than the mean;

The vertical temperature: 2300-0800 hrs in wintertime, less developed inversion; 2300-0800 hrs in summertime, more developed inversion than during average conditions;

Daily total insolation: summertime much higher insolation

than the mean, wintertime slightly higher than the mean.

The foregoing analysis has shown that the periods of the traverses have not matched average meteorological conditions in a number of ways. The effects of the deviation from normal probably compensate to a certain extent but the analysis of such effects would be long and involved. In assuming that the means for the periods of the traverses approximate the overall mean, one must recognize that there is a possibility of considerable error.

CHAPTER IV

THE FIELDWORK

A few temperature traverses over the city[1] had already been made when this study started in the fall of 1963. At first, the intention was to use the same instrument as had been used previously. This instrument was of the same type as that described later in section C. (p.31). Unfortunately, after a few traverses it was strongly suspected that the instrument was responding too slowly to sudden changes in temperature. Consequently, a new instrument was constructed. This new instrument (described in section C) responded rapidly enough according to both a special test and actual observations. To make it possible for the author to undertake the traverses alone, the instrument was connected to an automatic recorder. This system did not save any time. On the contrary, the time required to calibrate the instrument and evaluate the automatic recordings was much greater than the time required for the traverse. Another advantage with the instrument was that it gave a continuous report of the temperature during the traverse, while the earlier method gave the temperature only at specific locations. The new arrangement enabled the author to pick up some unexpected fluctuations, especially in the river valley. A mark was indicated on the chart for each of the 200 predetermined locations over an 80 km (50 mi)

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[1] Pers. comm. R.W. Longley, Edmonton.

[illegible]

[illegible]

[illegible]

[illegible]

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route in and around the city. The readings at all the locations were later calibrated to centigrade degrees and changed appropriately so they would be assumed to be temperatures at one constant time for each traverse.

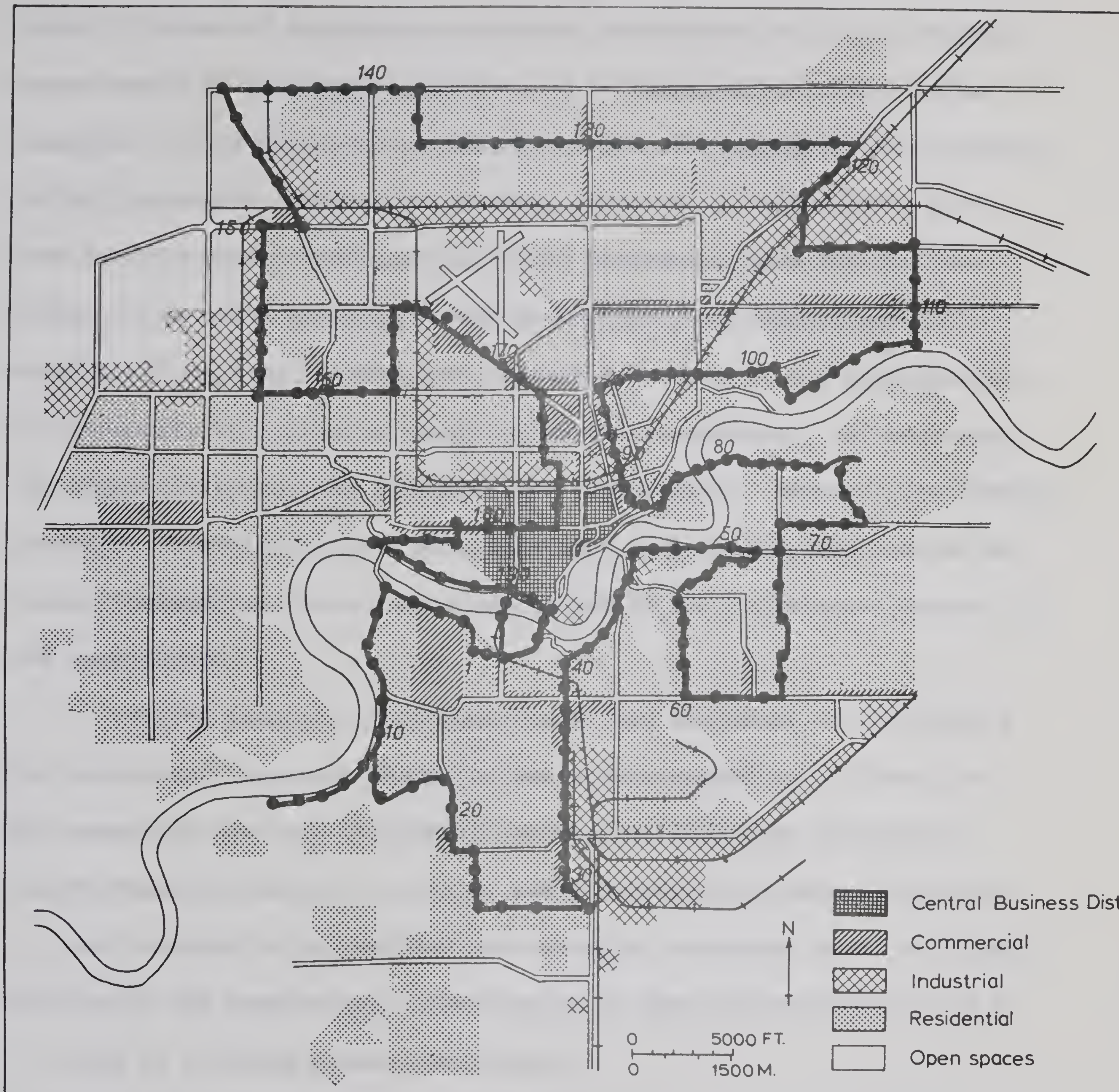
With this new instrument 42 completed temperature traverses were made during January, February, March, June and July 1964. Altogether, 8400 readings were later analyzed by a high speed computer.

A. Choice of the Route

The selection of the route entailed the following considerations:

1. It had to be rather short to enable reasonable reduction of the readings to one constant time, and thus not introduce too large an error (see section B), p. 26).
2. It had to include the various types of built-up areas (central business district, residential, commercial, industrial and open areas within the city, and the countryside).
3. Topographic features had to be included (ravines and the river valley).
4. If possible, areas in all the eight major compass directions should be included in order to get the temperature of the air before it enters the urban area.

Considering these points, the route as shown in Fig. 3 was selected. The large residential area to the west of the city (Jasper Place, see Fig. 1) was excluded, as a special temperature distribution investigation (3/11/63, see isotherm map Fig. 24) showed few relevant temperature characteristics. With the exception of a strong temperature increase on the outskirts of the aforementioned area, the temperature exhibited the homogeneity expected from an area having a uniform residential building pattern,



Legend: The temperature traverse route, where a dot indicates a location at which a mark was made on the recording chart. The traverse started at point marked 1 and was driven counter-clockwise back to the starting point.

Fig. 3. The temperature traverse route.

B. The Instrument Used for the Temperature Traverses

To get an adequate picture of the horizontal temperature distribution by means of temperature traverses throughout the city, numerous measurements of the temperature have to be taken within a short time interval. It is therefore necessary to have an instrument that responds quickly to minute temperature changes. Electrical thermometers have been used in most investigations of the horizontal temperature distribution of an urban area since mercury thermometers respond much too slowly. Electrical thermometers operate according to the principle that the conductivity of metals changes with the temperature. By measuring the conductivity one can determine the temperature. However, instruments operating according to this principle have to be calibrated against ordinary thermometers since the conductivity is only a relative measure of the temperature.

For the author's investigations it was necessary to construct a new instrument which was ready for use at the beginning of 1964. It was essential that the instrument perform the following functions:

(a) Be sensitive enough to pick up small temperature changes when the car on which it was mounted was moving at a maximum speed of 30 mph;

(b) Record the temperature automatically so that the traverses could be made by a single person, the driver;

(c) Record temperatures from -40°C to 40°C, and to read at least to an accuracy of 0.1°C;

(d) Not be so sensitive that the line on the recording chart would be so jagged that it would be difficult to read.

The temperature-measuring body should be well ventilated, but protected from direct sunlight. It was found that the best way to

satisfy these conditions was by using a sensitive probe in a Wheatstone Bridge circuit connected to an automatic recorder. This instrument was small, inexpensive, reliable and easy to mount on the car. By mounting the probe at 2 m (6.6 ft) height on the back bumper of the car, the influence from the car itself and vehicles in the immediate vicinity was minimized to an insignificant value.

The Probe. Although there are several types of electrical thermometers that can be used for temperature traverses, the most common ones are the thermistor type. A thermistor is a piece of semiconductor which, unlike metal and insulators, decreases in resistance as the temperature increases. This decrease in temperature is not linear. The probe or thermistor used in this study was made by Yellow Spring Instruments (Y.S.I.)[2] and referred to as Y.S.I. 408 or "Banjo". It had a "time constant" of 0.8 seconds. The term "time constant" is used to refer to the time required for a given probe to indicate $(1 - e^{-1})$ or 63 per cent of a sudden temperature change to which it is subjected. This is a standard method of expressing this type of response. The time required to adjust to a portion of a sudden change in temperature can be written: $y = 1 - e^{-x/k}$ (IV.1)

where y = the time required for a probe to show x per cent of a sudden temperature change

x = the per cent of change shown

k = a specific lag constant for each probe. For Y.S.I. 408, k is 0.40.

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[2]Yellow Spring Instrument Company, Yellow Spring, Ohio, U.S.A. Described in the company's catalog of October 1, 1963.

For the author's study the following example illustrates the efficiency of the Y.S.I. 408 probe:

If the car was driven at maximum speed within the city, how far would the car run before a sudden temperature change of 1°C would be recorded? If the probe was exposed to a sudden change in temperature of 1°C and an accuracy (see point c, page 26) of -.1°C is required, this means that the probe shall register 0.9°C (or 90 per cent of the sudden change). The time, y seconds, required for the probe to do this is according to (IV.1):

$$y = 1 - e^{-90/100\ 0.4} = 0.9 \text{ seconds}$$

If the car is driven at the maximum speed, 30 mi/h, this means that the car runs 12 m (40 ft) before the change is appropriately recorded. This maximum distance was assumed to be small enough for the author's investigations.

The line on the recording chart was never too jagged and could be read accurately. To protect the instrument body, the probe, from direct sunlight it was placed in a silver-colored tube which was pointing in the driving direction so that the speed of the car guaranteed proper ventilation.

<u>The Recorder.</u> The use of an automatic recorder had several advantages. The traverses could be made by the author alone. One received a continuous record of the temperature during the entire traverse. Subjective readings of an indicator needle which could easily be inaccurate due to speed or vibration were eliminated. The time at each reading on the recording chart could be determined exactly since the recording chart moved at a constant speed. The fastest recorder available to the author was made by Texas Instruments (T.I.), and is referred to as type R.S.R. The time required

for the recorder to show a sudden change was not found to be of significant influence on the conditions of temperature traverses with a car. The range of temperatures on the recording chart was only 10°C in order that the readings could be taken with an accuracy (see point c, page 26) of 0.1°C. It was therefore necessary to make alterations so that the instrument could be adjusted to the actual mean temperature and thus show $\pm$ 5°C from this temperature. The instrument was connected to the recorder by a resistance voltage divider. Several different resistances were tried here and the best combination seemed to be 100 ohms. and 330 ohms, giving voltage division of 1/4.3. The "gain" at the back of the recorder was set at 81. The vibrations in the car during driving did not influence the recorder. The recorder was electrically driven by the car battery and marks on the chart could easily be made. By closing the electrical circuit, the indicator pen immediately moved to one of the sides of the chart, hereby making a mark.

Instrumentation Technique. The varying resistance of the probe (R_b in Fig. 4) formed one part of a Wheatstone Bridge, a second part of the bridge was a potentiometer M, where the resistance could be changed between known values. The two other parts, R_a and R_b, were resistances with known fixed resistance. The current I to the recorder increased as the resistance R_p of the probe decreased. However, neither the change in the resistance of the probe with temperature nor the relation between I and R_p were linear, but the result of these two non-linearities was a nearly linear function. To get the required accuracy of the temperature readings in the range (see point c, page 26) -40°C to 40°C, a variable null-point potentiometer called a range control was installed. This control

determines the relationship between temperature and voltage. The energy source used was an ordinary 1.5 volt flashlight battery. The values of the resistances are given in Fig. 4. The range of the potentiometer M_S was converted into a 120-point scale, and the values of S thus refer to this scale. The range of the potentiometer M_R was converted into a 10-point scale to which the values of R refer. A switch was installed by which the current to the recorder could be broken thereby producing a mark on the recording chart. The disadvantage with the instrument was that several calibrations had to be made for different combinations of S and R.

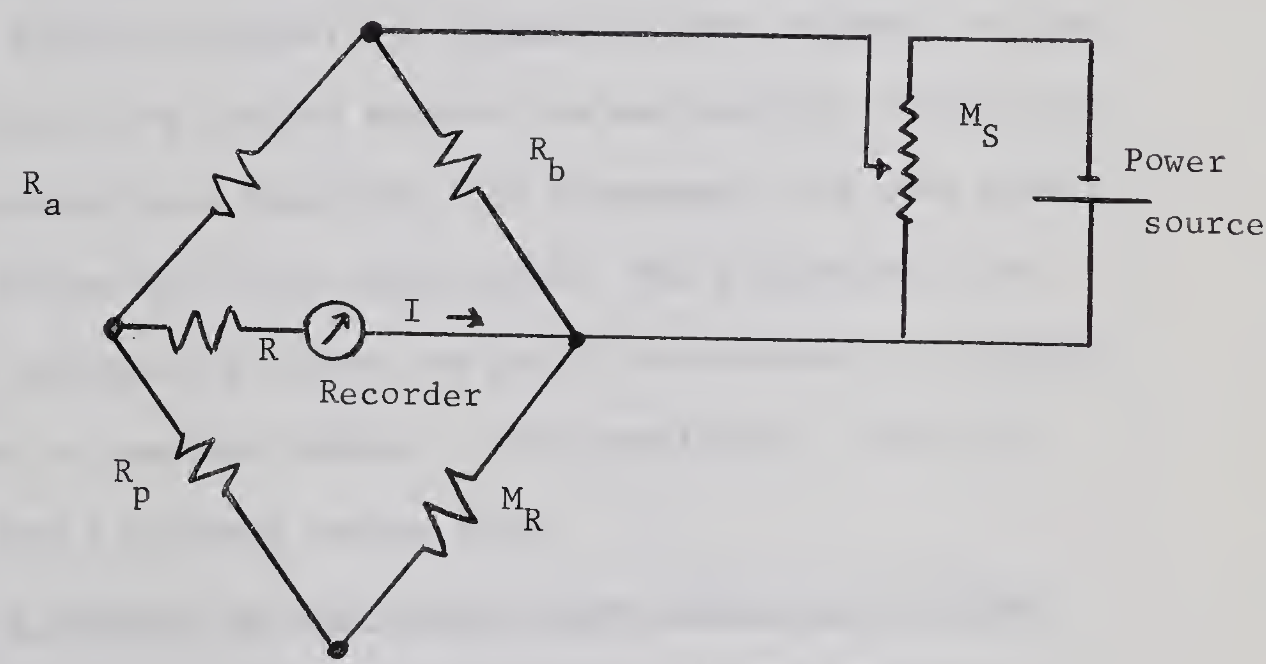

Fig. 4. Electrical Thermometer

Legend:

R_a, R_b = resistance of 1 kiloohm

R_p = the probe, Y.S.I., type 408 "Banjo"

M_R = potentiometer, Borg Instrument, Janerville, Wisconsin, U.S.A., model 2201 B, 100 kiloohm. The readings of this resistance referred to as the range, R.

M_S = potentiometer, Ohmite Instrument, model AB,500 ohm, no Cu - 5011. The réadings of this resistance referred to as the sensitivity, S.

I = the electrical current and its direction

R = resistance of 100 ohm and 330 ohm, giving a voltage division of 1/4.3.

Calibration. Before each traverse it was necessary to set the sensitivity, S, so that the temperature range on the chart was 10°C. For this purpose the diagram shown in Fig. 5 was constructed. In this diagram the correct setting of the sensitivity is shown for a given temperature. Next, the range, R, was set so that the indicator pen on the recorder was within the range of the chart. The values of the sensitivity, the range and the position of the pen on the chart were taken down. This made it possible later to construct the same temperature condition in a laboratory where the temperature could be measured with an ordinary thermometer. With these two settings of S and R, and the position of the pen on the chart the temperature of the calibration mixture (alcohol and liquid air) was changed, and the actual temperatures were plotted against the new position of the pen. As about 45 traverses were done with this instrument, the same number of calibration curves had to be constructed. The problem with the large number of calibration curves can partly be overcome by choosing a limited number of standard values on the sensitivity. The calibration curves had a slightly convex form.

C. Reducing the Readings to One Constant Time During the Traverse

As each traverse took about three hours, it was necessary to account for the general change in temperature during the traverse. This was done in the following way:

All the readings from the traverse were reduced to one constant time included in the traverse. Since the recording chart moved with a constant speed, it was possible to determine the time at which the separate marks on the continuous line of the recording chart were made. The general temperature change was supposed to be linear

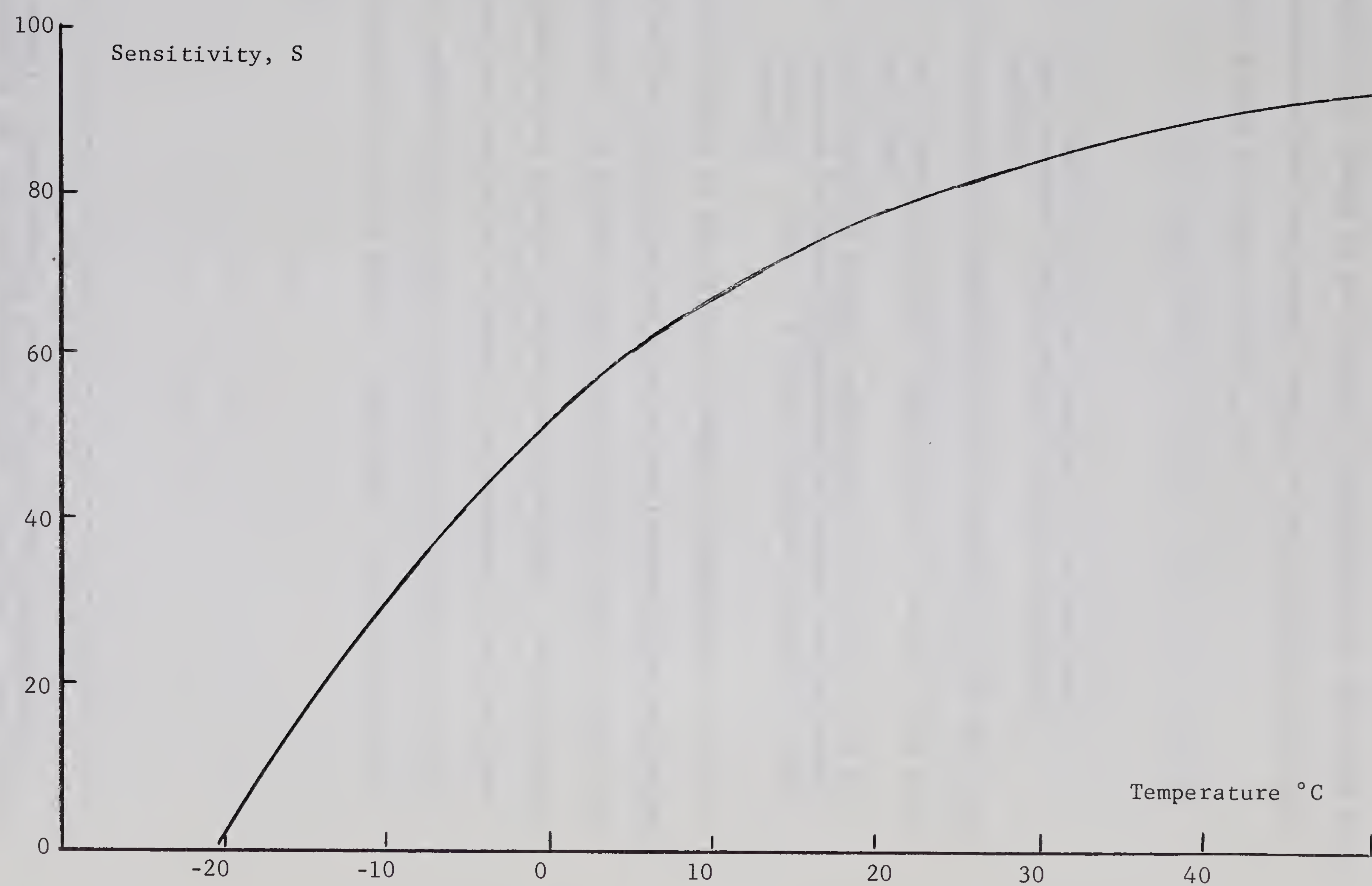

Fig. 5. Setting on the sensitivity dial for different temperatures.

between the hourly readings at the Industrial Airport (see Fig. 1). With this assumption the change in the "airport" temperature at each time was added or subtracted from the actual reading on the recording chart for each location during the route according to:

$$t_{i,c} = t_{i,t} + (t_{a,c} - t_{a,t}) \tag{IV.2}$$

where:

$t_{i,c}$ = the temperature at the location, i, at the time c (the constant time to which the whole traverse is reduced)

$t_{i,t}$ = the measured temperature at the location, i, at the time t

$t_{a,c}$ = the Industrial Airport temperature at the time c (a full hour time)

$t_{a,t}$ = the Industrial Airport temperature at the time t as determined by linear interpolation between the full-hour values at c and c + 1 hour. The time t occurs in this interval

The differences in the rates of change of temperature for different parts of the city during the time of the traverse were not assumed to be significant. An earlier investigation by the author[3] showed that similar assumption for Uppsala, Sweden, was justified. Though Edmonton has five times the population of Uppsala the assumption was concluded to be valid, especially as it was in practice not possible to account for the discrepancies in the general temperature for different parts of the city.

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[3]A. Daniels, "Undersökning av den sedan 1948 tillkomna bebyggelsens betydelse för temperaturutvecklingen i Uppsala," Unpublished fil.mag. thesis, Department of Geography, University of Uppsala, Sweden, 1962.

CHAPTER V

THE HORIZONTAL TEMPERATURE DISTRIBUTION OVER EDMONTON

The purpose of this part of the study was to find significant features in the horizontal temperature distribution over the city.

A. Statistical Methods Used in the Analyses of the Readings

The first thing to be calculated was the mean temperature of all readings from each traverse:

$$\bar{t}_{i,.} = \sum_{j=1}^{N} t_{i,j} / N \qquad \text{(V.1)}$$

where:

$\bar{t}_{i,.}$ = the mean temperature for the i:th traverse

$t_{i,j}$ = the temperature reading for the j:th location during the i:th traverse

N = the number of readings (200) during the traverse

The subsequent computation was the standard deviation for each traverse:

$$s_i^2 = \sum_{j=1}^{N} (t_{i,j} - \bar{t}_{i,.})^2 / (N - 1) \qquad \text{(V.2)}$$

where:

s_i = the standard deviation of the readings for the i:th traverse

The standard deviation (given for some traverses in Chapter IX) is the best measure of the temperature variation during the traverse.

Next data computed were associated with the temperature for specific locations. The difference between the actual temperature at each location and the mean traverse temperature was the value to be used in the analyses. These differences were found for all the tem-

[illegible]

perature readings from:

$$d_{i,j} = t_{i,j} - \bar{t}_{i,.} \qquad \text{(V.3)}$$

where:

$d_{i,j}$ = the difference in temperature between the j:th location during the i:th traverse and the mean temperature for the i:th traverse

The mean difference for all traverses for one location:

$$\bar{d}_{.,j} = \sum_{i=1}^{M} d_{i,j} / M \qquad \text{(V.4)}$$

where:

$\bar{d}_{.,j}$ = the mean temperature difference for the j:th location for all traverses

M = the number of traverses (42)

From these mean differences for each location, the mean difference isotherm map for the traverses was constructed (Fig. 6).

The corresponding standard deviation:

$$s_{dj}^2 = \sum_{i=1}^{M} (d_{i,j} - \bar{d}_{.,j})^2 / (M - 1) \qquad \text{(V.5)}$$

where:

s_{dj} = the standard deviation of the temperature differences for the j:th location for all traverses.

For the significance analysis of the difference in temperature at locations, it was decided to calculate the confidence interval for each location using the Student's t-test[1] for comparison of means. These intervals are limited by the upper and lower confidence limits:

$$\bar{d}_{.,j,u} = \bar{d}_{.,j} + s_{dj}\, t_{\alpha}\, M^{-1/2}$$

$$\bar{d}_{.,j,l} = \bar{d}_{.,j} - s_{dj}\, t_{\alpha}\, M^{-1/2} \qquad \text{(V.6)}$$

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[1]For instance: K.S. Keeping, Statistical Inference, New York, 1962, p. 179.

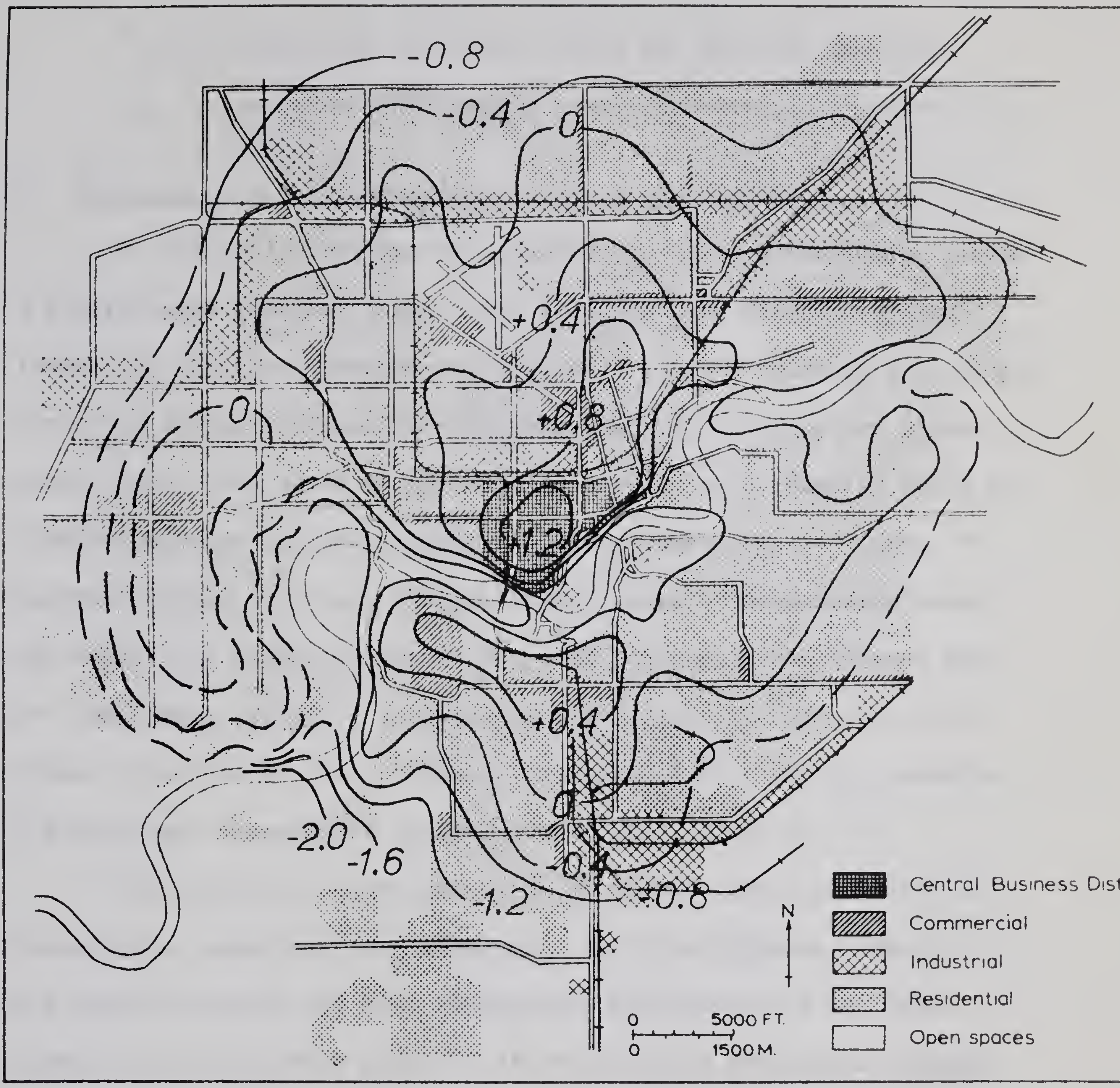

Fig. 6. Mean difference isotherm map for the traverses.
The equidistance is 0.4°C.

where:

$\bar{d}_{\cdot\cdot,j,u}$ = the upper confidence limit for the mean of the difference at the j:th location

$\bar{d}_{\cdot\cdot,j,l}$ = the lower confidence limit for the j:th location

t_{α} = the value of Student's t corresponding to a probability of α.[2]

B. <u>Analysis of the Horizontal Temperature Distribution</u>

By initially setting the value of t_{α} in (V.6) corresponding to a significance level of 5 per cent, the upper and lower confidence limits for the mean temperature difference of each location were found. Since the distance between any two consecutive locations was approximately equal, the means of the differences for each location could be compared without considering the distance between the locations. To determine where there was a significant change in temperature along the route, the mean differences for each location were compared with the confidence limits of the preceding location. If the mean difference fell outside the confidence interval of the previous location a significant temperature change had occurred (Fig. 7).

The influence of the direction of motion along the route was investigated using the same technique. In this instance, however, the locations where the mean temperature difference did not fall within the significance interval of the location immediately <u>following</u> were found. It was found that the direction of motion along the route was not connected with the change in temperature, as this analysis gave the same places of significant temperature changes as the previous analysis.

The next step in the analysis was to choose the t value corresponding to a significance level of 10 per cent and apply the same

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[2] *Ibid.*, p. 422.

[illegible]

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[illegible]

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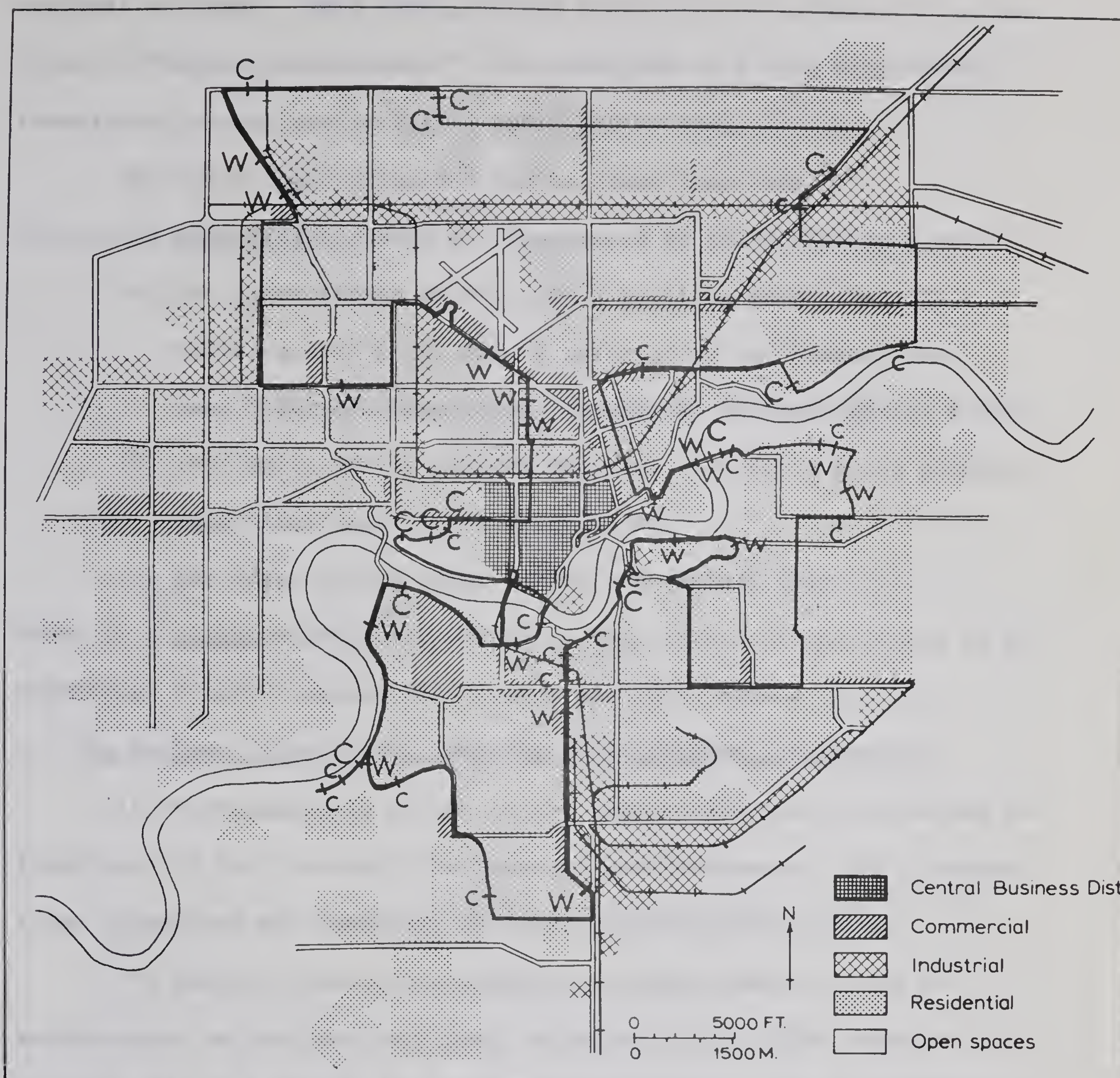

Fig. 7. Places along the route with a significant or slightly significant change in temperature. (Route was taken counterclockwise.)

C = significantly colder c = slightly significantly colder

W = significantly warmer w = slightly significantly warmer

—+— temperature traverse route, where a short cross on the line indicates the approximate location of the temperature change.

analysis as above. This level, 10 per cent, will be referred to as the level of "slight significance." The locations of slight significant temperature change are in Fig. 7 indicated by small letters.

The following conclusions can be drawn from Fig. 7:

There is a <u>significant</u> change in temperature at the following places:

(a) the outer limits of the city's built-up area (the city's built-up area is in Fig. 7 referred to as: Central Business District, Commercial, Industrial and Residential areas),

(b) the limits of the Central Business District and the connected commercial area to the north of it,

(c) the edges of the river valley and ravines (Fig. 1).

There is a <u>slight</u> significant change in temperature at: the limits of the commercial district around 82nd Avenue and 104th Street (Fig. 1).

C. <u>The Maximum City-Country Temperature Difference for Edmonton</u>

If no recognizable change in the temperature was found during the first part of the traverse, the traverse was terminated. This happened a few times, and was generally associated with overcast skies.

The maximum temperature difference between Edmonton and its surroundings varied from very small value to 11.5°C (2300 hours, 11/2/63, Fig. 12) during the temperature traverses. The mean maximum temperature differences for the traverses are shown in Table 10 (p. 52) for three-hour periods of the day. With the exception of the 2100-0000 hrs period which had a temperature difference 8.8°C, the city-country maximum temperature difference showed a daily variation with a maximum in early morning and a minimum in late afternoon. The maximum occurred earlier in the day in summer than in winter. The temperature difference in summer was on the average somewhat higher. These conclusions

from the temperature traverses are in accordance with Kratzer's.[3]

If the winter traverses are grouped around the times of the radiosonde ascents (0300, 0400, 0500, 0600 hrs and 1500, 1600, 1700, 1800 hrs), the mean temperature difference is (with the number of traverses in each group within brackets):

early morning (11): 3.3°C

late afternoon (9): 2.7°C

A comparison with the temperature difference between the Industrial Airport (Fig. 1) and the International Airport (19 km - 12 mi - to the south of the city) showed for the actual months the same variation:

Mean temperature differences between the Industrial Airport and the International Airport	Time of Day (MST)			
	0500	1100	1700	2300
Jan., Feb., March 1964	2.1	1.2	2.2	2.2
June, July 1964	1.2	0.1	0.4	1.7

D. Conclusions About the Horizontal Temperature Distribution Over Edmonton

Open Areas Within the City's Built-Up Area. Although there was a lowering in the temperature associated with open areas, these temperature decreases were not significant with the exception of ravines where cold air flows towards the river valley. However, the temperature of large open spaces within the city was measured only at the edge of the area but there might have been significantly lower temperatures further on in the area. Also the airport (Fig. 1) within

[3] A. Kratzer, Das Stadtklima, Braunschweig, 1956, p. 62.

the city seems to be an area with significantly lower temperatures than its surroundings.

Residential Areas. The greater part of the city is classified as residential. In general the houses are of one-story placed rather closely together, and the horizontal profile is even. This is also true for the temperature distribution within these areas. There is a slow uniform increase in temperature towards the more densely built-up and vertically expanded commercial areas.

Countryside. When approaching the city from its outskirts, there is a significant sharp increase in the temperature at the border of the built-up areas. The sudden change in temperature approximates the boundaries of the built-up area of the city rather well (Figs. 6 and 7). This fact has also been noted in other pertinent studies.[4]

Industrial Areas. Within the residential confines there are only small industrial areas. There was no indication of a definite difference in the temperature distribution from the residential areas.

The Central Business District and Connected Commercial Area to the North of It. The influence on the temperature by the Central Business District and connected commercial area to the north of it (Fig. 6) with their big buildings, is shown on most isotherm maps of the city (Chapter IX). This area is the warmest part of the

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[4]For instance: S.F. Duckworth and J.S. Sandberg, "The Effects of Cities Upon Horizontal and Vertical Temperature Gradients," Bull.Amer. Met.Soc. Vol. 35, 1954, pp. 198-207; T.J. Chandler, "London's Urban Climate," Geogr. Jnl., Vol. 128, 1962; H. Ermonds, Das Bonner Stadtklima, Bonn, 1954; H. Berg and H.K. Metzler, "Temperaturmessfahrten durch das Gebit der Stadt Hannover," Bioklimatische Beiblätter, Heft 1, 1934, pp. 111-114.

city and the temperature change at its boundary is significant.

Commercial Areas (excepting the Central Business District). The commercial areas, where the houses are closer and higher than in the residential areas, are warmer than the surrounding residential areas. There is a slight significant change in the temperature at the borders of the commercial development of 82nd Avenue and 104th Street (Fig.1). This is probably also the case with the other large commercial area in Jasper Place (Fig. 1), but as the traverses did not cover this area no measured difference can be stated. The other commercial areas are probably too small to produce a definite change in the temperature.

E. The River Valley

As the findings of the temperature in the river valley were especially interesting this special section will deal with them.
The steep-sided river valley is significantly colder than the general city area. In the river valley the temperature drops rapidly from the edges until half way down, but from here rises again. However, it generally never reaches the values at the top of the banks of the valley.

Brief Literature Summary of Weather Conditions in a River Valley. For Winnipeg, Manitoba, Einarsson and Lowe[5] also found that the temperature close to the river was higher than at locations further away from it. On one occasion Ermonds[6] investigated the wind systems in the

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[5] E. Einarsson and A.B. Lowe, "A Study of Horizontal Temperature Variations in the Winnipeg Area at Nights, Favouring Radiational Cooling," Canada, Dept. of Transport, Met. Branch, Tec.Cir. Series 2647, Tec.214, 1955.

[6] H. Ermonds, Das Bonner Stadtklima, Bonn, 1954.

river valley in Bonn, Germany. From a layer with weak winds at the bottom, the wind increased with height in three steps and changed from a direction parallel to the river to the prevailing wind direction on the plain. Klassen,[7] too, revealed the following in a river valley study of Edmonton:

(a) Except during strong insolation and strong prevailing winds, there was a distinct difference between the winds of the river valley and those of the plain;

(b) There was a drainage of cold air down McKinnon Ravine (see Fig. 1);

(c) The "down valley wind" was much less dependent on the prevailing wind than the ravine wind. These two wind systems disappeared suddenly as the prevailing wind reached 9 mi/h. The down valley wind increases in velocity up to a certain altitude in the river valley.

The wind systems in a valley of the size of the Edmonton river valley and larger, have been well described by Davidson.[8] He differentiates between three systems in the valley:

(a) A thin layer at the walls of the valley, 30-60 m (100-200 ft) thick, with occasional strong air movements, the mean movement, however, is zero;

(b) The valley wind, parallel to the river. The air stream

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[7] W. Klassen, "Micrometeorological Observations in the North Saskatchewan River Valley at Edmonton," Canada, Dept. of Transport, Met. Branch, Tec.Cir.Series 3652, Tec-408, 1962.

[8] B. Davidson, "Valley Phenomena and Air Pollution Problems," J. Air Poll., Vol. 11, No. 8, 1964, pp. 364-369.

[illegible]

is down the valley. It was most strongly developed during the inversion situation and more frequent in the summer than in the winter.

(c) The prevailing wind system. At a certain speed this system destroys the other ones.

Interpretation of the Temperature Distribution in the Edmonton River Valley. The weather conditions under which the traverses were undertaken were such that specific valley wind systems could develop according to Klassen[9] and Davidson[10]; these weather conditions were associated with moderate winds, no or moderate insolation and in general a ground inversion. From research literature and the temperature traverses the author agrees with Klassen that there were two specific air systems in the river valley:

(a) The valley wind system. A cold stream of air resulting from the drainage of cold air from the plain into the river valley. This drainage was also indicated by a cold air stream along the ravines both within and without the city. Since the river valley's impact on the city temperature distribution was greater in the western part of the city[11] this system is draining in the direction of the current of the river and is not fed by air from the city. The air from this system should flow along the bottom of the valley as it is heavier than the surrounding warmer air. Generally this is not the case. The reason for this is explained by the following air system.

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[9] Klassen, op.cit.

[10] Davidson, op.cit., pp. 364-369.

[11] See isotherm maps, Chapter IX.

(b) <u>The river heated air system</u>. The larger part of the river within the city was not frozen during any of the traverses. The water of the river heated the air above the water surface. The influence of the river could be noted as high up as the High Level Bridge (see Fig. 1). In crossing this bridge during the traverses there was a slight decrease at the approaches and the temperature rose to a maximum in the middle of the bridge. The increase was not so large as down in the river valley. On both, the Low Level Bridge and the 105th Street Bridge (see Fig. 1), a slightly significant rise of the temperature at the middle of the bridge was found. This system forced the valley wind system of cold air to the sides of the river valley. The decrease with height of temperature from the river bottom up to the High Level Bridge was on the average that of dry adiabatic lapse rate.

In summing this up: In situations with moderate winds and insolation and unfrozen river there are two specific air systems developed in the Edmonton river valley. As one drives down the river valley one first goes through a cold air drainage system at the side - the valley wind - before reaching the warm river-heated air system at the bottom of the river valley.

CHAPTER VI

THE VERTICAL TEMPERATURE DISTRIBUTION OVER AN URBAN AREA

A. Literature on Vertical Temperature Distribution over an Urban Area

In comparison with the number of studies of horizontal temperature over an urban area the number of vertical temperature studies are relatively few.

One of the earliest studies of the vertical temperature over an urban area was made by Fritsche and Stange[1] in Leipzig. By means of thermometers on an 80 m (262 ft) high radio tower they were able to get a series of continuous readings. They found two layers in the temperature distribution, but on the average, according to a diagram in Kratzer's book,[2] the temperature in the lowest part decreased with height as that defined as the dry adiabatic lapse rate (1°C/100 m). The height of this layer varied depending on the time of the day. It was lowest in early morning and highest in early afternoon. During the afternoon the lowest part was strongly heated, resulting in a superadiabatic lapserate in the lowest decameters.

By means of thermistors mounted on a balloon cluster Duckworth and Sandberg[3] were able to obtain information on the vertical

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[1]W. Fritsche and R. Stange, "Vertikaler Temperaturverlauf über einer Gross-stadt," Beitrag zur Physik der freien Atmosphere, Heft 23, 1936, pp. 95-110.

[2]A. Kratzer, Das Stadtklima, Braunschweig, p. 88.

[3]F.S. Duckworth and J.S. Sandberg, "The Effect of Cities Upon Horizontal and Vertical Temperature Gradient," Bull. Amer.Met.Soc. Vol. 35, 1954, pp. 198-207.

temperature distribution over urban areas compared with that of the surrounding countryside. Instruments were sent aloft simultaneously from three cities (San Francisco, San Jose, and Palo Alto, California) and their surrounding countryside. The profiles reported by these instruments suggested that the heat from the city tended to destroy the nocturnal inversion over the city in the lowest few hundred feet, whilst the inversion persisted aloft.

Generally TV towers cannot be utilized for urban vertical temperature studies because they are located in the open country. However, this is not the case in Louisville, Kentucky, where a tower is located in the center of the city. This tower was used by DeMarrais[4] and he concluded:

> The vertical temperature differences observed at night over Louisville are considerably different from those observed over non-urban areas. Whereas surface inversions regularly occur in non-urban areas they are comparatively rare in urban complex. During half of the hours at night, a lapse rate between isothermal and adiabatic in the 60 to 524 foot layer is observed, and during 30 per cent of the night hours a discontinuous lapse rate in which the lower part of the layer is less stable than the upper part is observed.

In Montreal, Summers[5] found no occasion with ground inversion over the city during a series of observations during anti-cyclonic weather conditions.

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[4] G.A. DeMarrais, "Vertical Temperature Differences Observed Over an Urban Area," Bull. Amer.Met. Soc., Vol. 35, 1961, p. 198.

[5] P.W. Summers, "An Urban Heat Island Model, Its Role in Air Pollution Problems, with Applications to Montreal," presented at the First Canadian Conference on Micrometeorology, Toronto, 1965.

For Berlin, Flach[6] concluded..."(there was) evidence that even during persistent inversions the lowest decameters are rapidly mixed...."

Measurements from a helicopter over Cincinnati, Ohio, have been analyzed by McCormick and Baulch.[7] On several occasions lapses of temperature were found from the surface up to a height of 100 to 150 m (330 to 490 ft) with stable lapse rates above.

Thus, there is increasing evidence that large urban areas influence the vertical temperature up to a height of some hundred meters, so that on the average the lapse rate over the city is near that of dry adiabatic lapse rate.

B. The Urban Heat Island Model

The degree of vertical mixing of air is determined by the turbulence of which there are two types: thermal and mechanical. Thermal turbulence is caused by the heating of the air, generally close to the ground. This heated air will rise if initial displacement is present. Mechanical turbulence is caused by obstacles in the path of an air stream. In general, over country with low vegetation and little relief the air stream is laminar as the two kinds of turbulence are at a minimum. The thermal turbulence is not well developed as surfaces covered with low vegetation do not heat up as easily as concrete and asphalt. The mechanical turbulence is small as there are relatively few objects to interfere with the air stream. The situation over the city is different. Here streets and buildings act

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[6] E. Flach, "Über kontinuerlich durchgefürte Kernzahlbestimmungen, ihre meteologische und bioklimatische Bedeutung," Beitrag der Deutche Wetterdienst, U.S. Zone, Heft 38, 1952, pp. 238-264.

[7] R.A. McCormick and D.M. Baulch, "The Variation with Height of the Dust Loading over a City as Determined from Atmospheric Turbidity," J. Air Poll. Control Assoc., Vol. 12, 1962, p. 492.

as heaters for the surface air, which therefore becomes unstable. Buildings also act as obstacles to wind and thus the mechanical turbulence is much greater than over the relatively level country. Thus when the relatively laminar air flow enters the city, the lower layers are mixed. A model to calculate this height up to which the air is caused to mix by the city has been developed by Summers.[8] In this model - the urban heat island model - it is assumed that, because of the turbulent mixing of the air, the vertical temperature distribution over the city is that of dry adiabatic lapse rate up to a certain height - the mixing height - above which the air is no longer influenced by the city. The assumption is in accordance with actual measurements (see previous page). With this assumption the mixing height can be calculated from:

$$t_h = t_{co} - h\gamma$$
$$t_h = t_{ci} - h\Gamma \qquad \text{(VI.1)}$$

where:

t_h = the temperature at a height, h, where the city no longer influences the temperature (the mixing height). Thus this temperature is the same over the country and the city.

t_{co} = the ground temperature over the country

t_{ci} = the ground temperature over the city

γ = the lapse rate over the country

Γ = the lapse rate over the city (= dry adiabatic)

h = the mixing height

The two equations in (VI.1) can be combined:

$$h = (t_{ci} - t_{co}) / (\Gamma - \gamma) \qquad \text{(VI.2)}$$

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[8] Summers, op.cit.

If meters and degrees Celsius are used (gives $\Gamma = 0.01$):

$$h = (t_{ci} - t_{co}) \,/\, (0.01 - \gamma) \qquad \text{(VI.3)}$$

Thus the mixing height is the intersection between the dry adiabat from the observed ground temperature in the city, and the observed temperature profile over the country. The "<u>maximum mixing height</u>" is defined as the greatest mixing height over the city, and computed by choosing t_{ci} in (VI.2) as the highest temperature in the city. This concept is illustrated in Fig. 8.

The mixing height varies from place to place within the city. It increases from zero at the borders of the city's built-up area (where the city temperature excess is nil) to a maximum in the warmest part of the city (where the temperature excess is at a maximum).

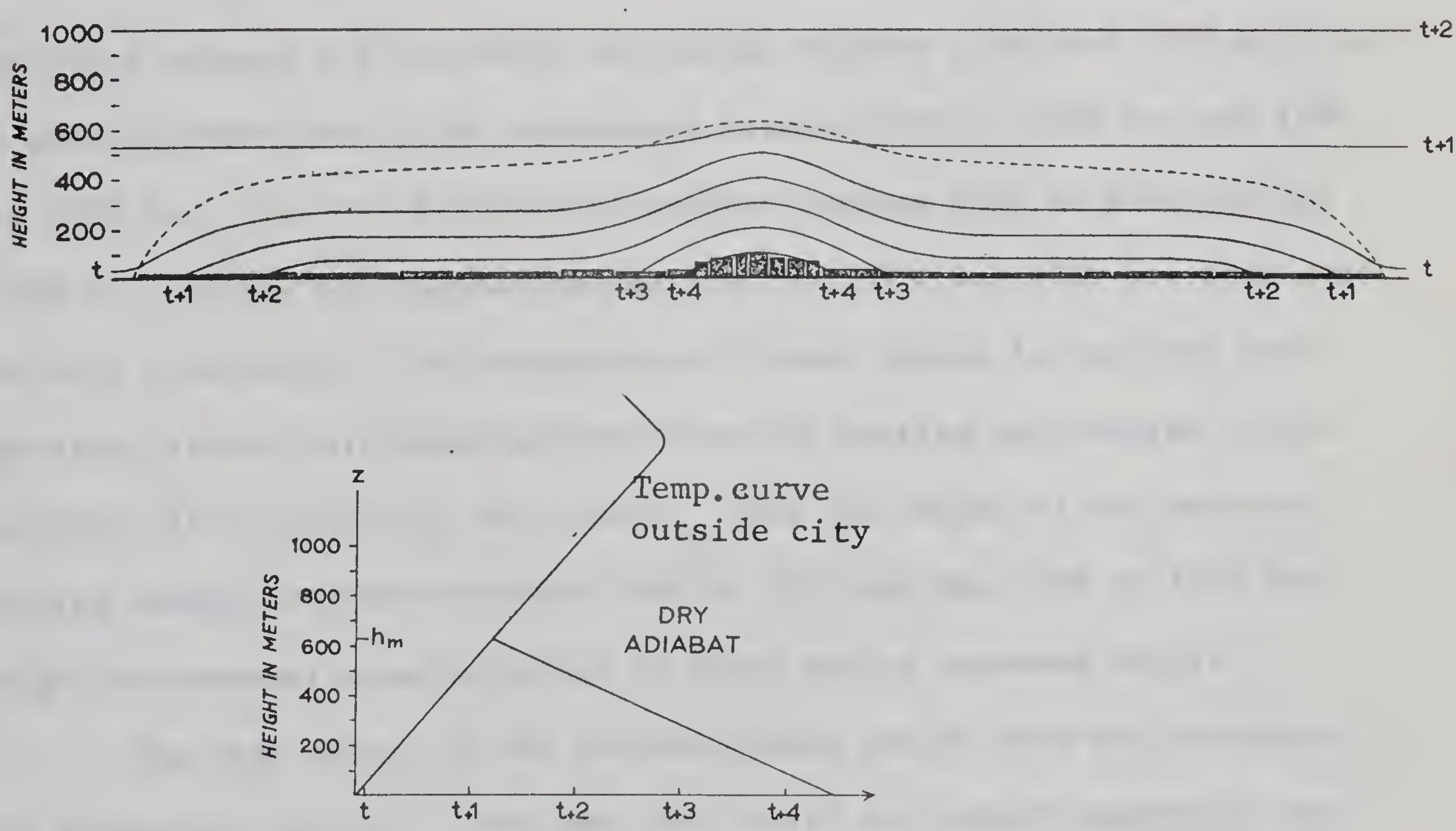

Fig. 8. The urban heat island and its maximum mixing height.

Legend: _ _ _ = the mixing height or the top of the urban heat island
——— = isotherms at 1°C intervals
h_m = the maximum mixing height

[illegible]

[illegible]

A temperature cross-section over the city would thus appear as the top of a pillow of warm air over the city. This pillow of warm air is called "the urban heat island."

If the temperature over the countryside decreases with height as that of dry adiabatic lapse rate (1°C/100 m) the mixing height would be infinite. In this case it is obvious that the urban heat island model cannot be applied. However, these occasions are, especially in winter, relatively rare.

C. Application of the Urban Heat Island Model to the Temperature Traverses

The maximum mixing height, calculated for each of the 42 temperature traverses, from (VI.3) are shown in Table 11 (page 62). It is necessary to know the lapse rate over the country when the mixing height is calculated. In this study the country lapse rate was found by linear interpolation between the two daily radiosonde reports (0500 and 1700 MST) for traverses other than those undertaken between 0300 to 0700 hrs and 1500 to 1900 hrs. For the traverse undertaken between 0300 to 0500 hrs and 1500 to 1900 hrs the radiosonde reports from 0500 and 1700 hrs were used without alteration. The assumption of linear change in vertical temperature is not very satisfactory since the heating and cooling of the surface air is generally not linear. Thus the values of the maximum mixing height for hours outside 0300 to 0700 hrs and 1500 to 1900 hrs might be somewhat uncertain, but no other method appeared better.

The mean values of the maximum mixing height from the traverses, by three-hour periods of the day, for winter and summer separately are given in Table 10. For the traverses the following conclusions can be made:

TABLE 10 - MEAN CITY-COUNTRY TEMPERATURE DIFFERENCES, MEAN MAXIMUM MIXING HEIGHT AND MEAN AMOUNT OF HEAT REQUIRED FOR THE HEAT ISLAND, BY THREE-HOUR PERIODS, FOR THE TEMPERATURE TRAVERSES

Winter[2] Hours (MST)	Number of traverses	Maximum city-country temperature difference, °C	Maximum mixing height (m)	Energy required for the heat island[1], 10^9 BTU
2100-0000	2	8.8	531	670
0000-0300	7	3.6	316	125
0300-0600	5	4.0	241	117
0600-0900	8	2.6	201	50
1400-1600	2	1.5	669	181
1700-1900	7	2.8	478	139
Mean		3.4	348	146
Summer[3]				
2100-0000	2	3.4	2304	1927
0000-0300	2	5.3	350	245
0300-0600	6	4.1	213	159
1100-1400	1	2.1	3129	1471
Mean[4]		4.0	247	180

[1]24 times the calculated hourly value

[2]January, February and March

[3]June and July

[4]With the exception of the three highest values for the maximum mixing height and the heat for heat island

(a) The maximum mixing height had a definitive diurnal variation, with a minimum in early morning (about 200 m - 650 ft - winter and summer) and a maximum in the afternoon (about 600 m - 2000 ft - in winter).

(b) The maximum mixing height at night is the same in winter and in summer:

0300-0700 hrs in winter; 224 m (734 ft), 12 traverses,

0300-0700 hrs in summer; 212 m (695 ft), 6 traverses.

Using minimum temperatures from two fixed stations in Montreal, Summers[9] found the early morning mixing height over McGill University, located 6 km (3.8 mi) from the city's border, to be significantly higher in winter (224 m - 734 ft) than in summer (133 m - 437 ft).

The reason for the difference between Summers' findings and those for Edmonton might be found in the different methods used to estimate the city effect on the temperature and different annual variation of meteorological parameters used.

D. <u>The Shape of the Urban Heat Island over Edmonton</u>

The horizontal distribution of temperature as concluded from the traverses can be described as follows: at the edge of the city's built-up area a sharp increase of the temperature, then a slow increase to the edge of the central business district where a second sharp gradient is present. If the mixing height, calculated from (VI.2) for every point along a cross-section of the city with this horizontal temperature distribution is plotted, the result is as shown in Fig. 8. The three-dimensional shape of the heat island can best be approximated by an ellipsoid, with the exception of the center dome over the central business district. There are, of course, several irregularities in the horizontal temperature distribution, but these are probably evened out at the top of the heat island. If the shape of the heat island is approximated by an ellipsoid the amount of energy required to maintain it can be calculated.

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[9] Summers, <u>op.cit</u>., Table II.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

E. Calculation of the Energy Required to Maintain the Ellipsoidic-Shaped Heat Island

An adequate mathematical expression to approximate the horizontal temperature as described above for a cross-wind section through the city center was found to be:

$$\frac{\Delta t^2}{d^2} + \frac{y^2}{b^2} = 1 \qquad \text{(VI.4)}$$

where:

Δt = the temperature excess at a point y length units from the city center

d = the temperature difference between the city center and the countryside (= the maximum temperature difference)

b = half the cross-wind width of the city through the center (see Fig. 9)

If the temperature at the ground on the countryside is t_o, the temperature at a height z above this point is $t_o - \gamma z$, where γ is the lapse rate over the country. The temperature at the ground at a point, y length units from the city center within the heat island, is, according to (VI.4) $t_o + d\,(1 - y^2/b^2)^{1/2}$. At a height z above this point the temperature is: $t_o + d\,(1 - y^2/b^2)^{1/2} - z\Gamma$, where Γ is the lapse rate over the city. Thus the temperature excess dt_{zy} at the level z above this point within the heat island is:

$$\begin{aligned} dt_{zy} &= t_o + d\,(1 - y^2/b^2)^{1/2} - z\Gamma - (t_o - z\gamma) = \\ &d(1 - y^2/b^2)^{1/2} - z\,(\Gamma - \gamma) = \\ &d(1 - y^2/b^2)^{1/2} - \frac{zd}{h} \end{aligned} \qquad \text{(VI.5)}$$

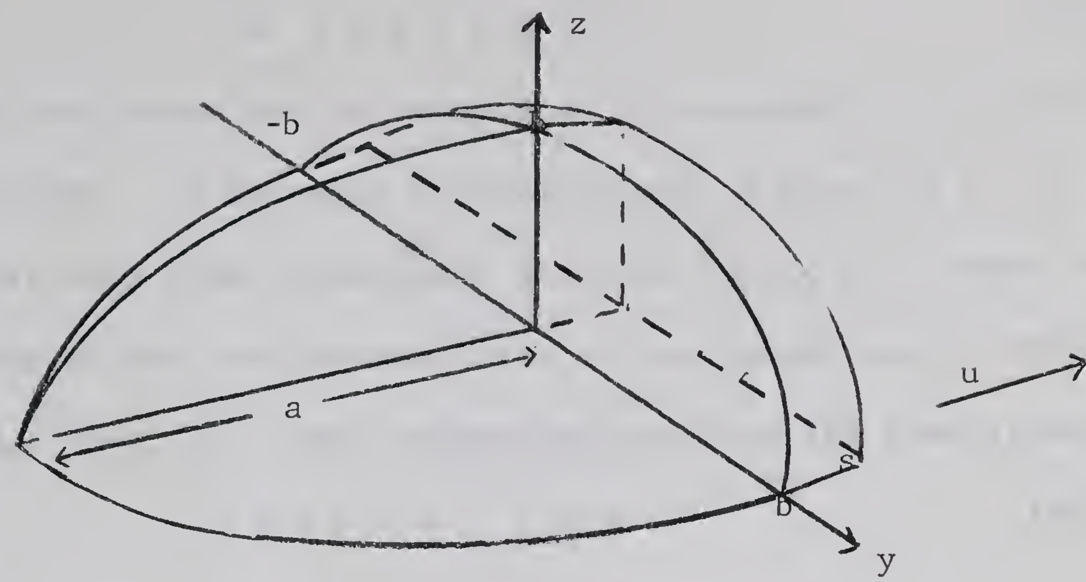

Fig. 9. The heat island with the explanation of symbols used for calculations

Legend: a = the distance from the edge to the center of the city in the direction of the prevailing wind

b = the crosswind distance from the edge to the center of the city. The center of the city is assumed to be in the middle of the cross-section

h = the maximum mixing height

s = the length of the air volume heated during one time unit

u = the wind direction

The total energy required to maintain a heat island of this cross-section through the city center and with a length of one unit, is found by integration of (VI.5) over the cross-section:

$$H_1 = \int_{-b}^{b} \int_{0}^{h(1-y^2/b^2)} \left[d\,(1 - y^2/b^2)^{1/2} - z\,d/h\right] c_p \rho \; dz\, dy \qquad \text{(VI.6)}$$

where:

H_1 = the energy required to maintain the heat island per unit length

ρ = the density of the air

c_p = specific heat of air at constant pressure

Equation (VI.6) can be integrated and gives:

$$H_1 = 2\ b\ h\ d\ c_p \rho /3 \qquad \text{(VI.7)}$$

The wind speed can be assumed to be constant with height[10] within the heat island. If the wind is blowing with a speed of u, the energy required per unit time to maintain the heat island is u times the energy required for the cross-section of one length unit. Steady state is assumed. Thus, the total energy required for the heat island:

$$H = 2\ b\ h\ d\ c_p \rho\ u/3 \qquad \text{(VI.8)}$$

where:

H = the energy required per unit time to maintain an ellipsoidic-shaped heat island as shown in Fig. 9 at a wind speed of u, and a maximum temperature difference of d degrees between the city and the country. As can be seen on the figure this heat is only received from the upwind half of the city.

F. The Ellipsoidic-Shaped Heat Island Model Applied to Edmonton

For each of the 42 temperature traverses in Edmonton during the first half of 1964 the energy necessary to maintain the measured heat island was calculated from (VI.8). The following values of the variables were used:

u = the wind speed and direction taken from weather reports of the Industrial Airport (Fig. 1)

d = the difference between the highest and the lowest temperatures from the traverse. The temperatures in the river valley outside the city were generally the lowest ones, but they were not used since they were assumed not to be representative for the country temperature.

b = half of the crosswind width of the city. Although this varies with different wind directions, the city was assumed to be circular with a radius, b, of 6400 m (4 mi) (Fig. 1).

ρ = the density of the air can be expressed as: $\rho = p/RT$, where p is the pressure, T the absolute temperature, and R the gas constant for air = $6.87 . 10^{-2}$ cal.gm. The values of p were taken from the barograph at the Department of Geography, University of Alberta (Fig.1), the values of T were taken as the average temperature for the traverse.

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[10] Summers, op.cit., p. 4.

The result of the energy calculation for each traverse is given in Table 11. The mean values are shown in Table 10 by three-hour periods and seasons. The calculated hourly values of the required energy in the tables are multiplied by 24 hereby enabling comparison of the energy required to maintain the heat island for a 24-hour period with the daily energy received from radiation and gas consumption.

The three highest values of the energy required in summer: $1301 \cdot 10^9$ BTU (4/6 2200 hrs); $1471\ 10^9$BTU (20/7 1300 hrs) and 2552 10^9 BTU (20/7 2100 hrs) are probably too large, possibly because of an error involved in using linear interpolation between the two daily radiosonde reports of the vertical temperature (see page 51) and the fact that the model could not well be applied in these cases since the lapse rates over the country were close to that of dry adiabatic (see page 51).

With the exception of these three values, the energy required for the heat island varied within a fraction of ten. It showed a diurnal variation with maximum in the afternoon and a minimum in the early morning. This variation can be explained by the fact that during the day there is an increasing amount of stored heat from solar radiation available.

The seasonal difference shows a maximum of energy available in summer and a minimum in winter. Thus the energy from the gas consumption for heating purposes is not sufficient to compensate for the decreased amount of solar energy in winter.

CHAPTER VII

DISCUSSION OF THE PHYSICAL BASIS OF THE HEAT ISLAND

There are two classes of factors combining to cause the heat island:

(a) heat sources, more extensive in urban areas;

(b) climatic conditions.

The Heat Sources

These are of two kinds: artificial and natural. The artificial heat sources are mainly associated with space heating, domestic needs, industrial processes and vehicular traffic. The energy for space heating[1] is generally assumed to be proportional to the heating degree-days. The heating degree-day is defined as the departure of the mean daily temperature below 18°C (65°F). Robertson[2] found that the relation between gas consumption and temperature for Edmonton could be written: Gas consumption = $-926000 + 9190\,T - 20.7\,T^2$, which is an almost linear relationship. Gold[3] estimates that the heat released by one car is 2.5×10^5 BTU per hour. This indicates that the heat from the traffic is not an unimportant factor for the heat balance of a city. The natural sources are mainly of radiation nature. During daylight, walls and streets absorb much more of the solar radiation than does the vege-

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[1] P.W. Summers, "An Urban Heat Island Model; Its Role in Air Pollution Problems, with Applications to Montreal," presented at the First Canadian Conference on Micrometeorology, Toronto, 1965, p. 16.

[2] G.W. Robertson, "Low Temperature Fog at Edmonton, Alberta, as Influenced by Moisture from Combustion of Natural Gas," Quart. J. R. Met. Soc., Vol. 81, 1955, p. 194.

[3] L. Gold, "A Computing of Air Pollution," Quart. J. R. Met. Soc., Vol. 80, 1954, p. 273.

[illegible]

tation-covered ground in the countryside. The absorption of heat is assumed to be a direct function of: the specific heat capacity times the thickness of the material times the square root of its specific heat conductivity.[4] Schmidt[5] gave some values for the product of these quantities:

Steel	Granite	Sandy Soil	Sand	Ice	Snow	Water
0.32	0.048	0.033	0.015	0.032	0.0017	0.039

Since the city contains a large proportion of granite in comparison to the surrounding country, the heat absorption capacity is correspondingly greater. This will result in a delay in the rise of temperature in the morning but will also prevent fast cooling at night. Especially large is the difference in the absorption capacity between the city and the country when the ground is covered with snow, as the snow in the city is partly removed, and to a much greater extent covered with dirt. These two factors both make the absorption higher in the city.

The moisture content of the ground is also of importance to the heat absorption. The well-drained city makes temperature changes more rapid and extreme than in the country. However, this is more than compensated for by other climatic factors. Fog and dust moderate the changes so the dryness of the city surface results only in an absolute increase of the city temperature.[6] There are large annual and diurnal variations in the solar radiation and in the terrestrial

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[4]A. Kratzer, Das Stadtklima, Braunschweig, 1956, p. 66.

[5]W. Schmidt, "Der Massenaustausch in freien Luft und verwandte Erscheinungen," Probleme der kosmischen Physik, Band 7, 1926, p. 34.

[6]Kratzer, op.cit., p. 67.

radiation. The latter is absorbed to a much higher degree by the "horizontal off-screening"[7] in the city than in the country. Horizontal off-screening means that the terrestrial radiation (radiating in all directions) is absorbed by objects adjacent to the emitting source. This is a much more common phenomenon in the city with its high buildings than in the relatively flat countryside.

Climatic Conditions

The much higher content of aerosols in the air over the city is a factor in building the heat island. Kratzer states"...Die erste and wichtigste Ursach des Wärmeüberschusses der Stadt liegt in ihrer Dunsthaube...."[8] However, some other authorities do not agree. Landsberg[9] states."...The conviction of the author is that the absorption effects contribute in reality only in a minor way to the temperature rises that have been observed in cities." Sheppard states that there is a significant absorption of both long and short wave radiation by air pollution. The sun heats the polluted layers 1-2°C. The absorption and associated emission of terrestrial radiation by particulate matter appears to be capable of cooling the air over the haze layer by a few degrees Celsius.[10]

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[7]Å. Sundborg, Climatological Studies in Uppsala, Uppsala, 1951, p.96.

[8]Kratzer, op.cit., p. 66. Translated: The first and most important reason for the heat excess in the city lies in its envelope of air pollution.

[9]H.E. Landsberg, "City Air - Better or Worse." Symposium, Air Over Cities, SEC Technical Report A62-5, 1961, p. 7.

[10]P.A. Sheppard, "The Effect of Pollution on the Radiation in the Atmosphere," Int. J. Air Poll., Vol. 1, 1958, p. 42.

The humidity of the air also influences the temperature. An increase in the humidity content decreases the rates of cooling and heating of the air. Ermonds[11] found the absolute humidity in the city somewhat lower than that of the country. The difference is so small it probably affects the heat island only in a minor way.

The cloud cover is an important factor affecting the heat island. This has been documented by both Ermonds[12] and Sundborg.[13] By means of regression analysis they found the temperature difference between the country and the city to be negatively correlated with the cloud cover. At night time they found the correlation coefficients to be relatively large; in the day small.

A. Evaluation of the Factors Determining Edmonton's Heat Island

In Table 11 the amount of energy necessary to maintain the heat island as observed for each traverse is presented. The heat is the amount required to maintain the heat island during 24 hours. For the day of each traverse the gas consumption was obtained from Northwestern Utilities, which delivers all gas burnt in the city. The figures in Table 11 show the gas consumed for domestic, commercial purposes, and space heating, plus the gas used by light industries within the city. As can be seen in the table, consumption, as expected, is at a maximum in winter and at a minimum in summer, when the consumption figure is about 20 per cent of the winter figure. The gas used in winter is: for domestic and commercial purposes about 15

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[11] H. Ermonds, Das Bonner Stadtklima, Bonn, 1954.

[12] Ibid., p. 50.

[13] Sundborg, op.cit., p. 84.

TABLE 11 - THE HEAT ISLAND, AS DETERMINED FROM THE TEMPERATURE TRAVERSES

Day (1964)	Hour	Maximum Mixing Height m	Daily Calculated Heat 10^9 BTU	Daily gas consumption 10^9 BTU	Daily sun radiation 10^9 BTU	Air pollution COH/1000 ft air	Wind-speed mi/h	Cloud-cover tenths
11/1	00	269	37	187	32	0	4.5	8.6
12/1	02	114	49	170	24	0.23	10.0	0
15/1	00	271	240	159	22	0.43	5.5	0
15/1	18	378	208	159	127	0.55	7.0	5.6
16/1	08	131	23	289	127	0.68	4.0	9.9
17/1	18	301	63	153	37	0.23	10.5	7.4
19/1	18	326	124	160	26	0.33	11.0	8.2
22/1	18	467	34	207	41	0.68	2.0	0
11/2	17	532	60	144	36	0.55	10.0	1.4
11/2	02	190	32	144	32	0.23	8.0	5.0
11/2	23	400	790	144	36	0.10	8.5	0.9
12/2	03	284	253	160	36	0.33	6.5	0
13/2	01	225	128	146	49	0	13.0	5.4
24/2	01	509	159	158	91	0	26.0	10.0
4/3	06	154	16	163	88	0	16.0	10.0
7/3	17	632	60	159	120	0.80	9.0	2.0
8/3	02	632	232	148	120	0.23	5.5	4.6
8/3	19	712	421	148	84	0	13.0	9.2
9/3	07	129	38	155	84	0	4.0	9.6
10/3	04	177	37	152	111	0.80	6.5	8.4
11/3	04	210	142	145	100	0	6.5	5.2
12/3	05	211	41	139	107	0.43	6.0	0.8
13/3	06	248	68	132	132	0.55	5.0	2.2
14/3	15	732	294	127	117	0.23	9.5	4.8
16/3	06	310	67	184	70	0	10.0	9.8
18/3	06	140	20	141	91	0.10	7.0	2.6
20/3	06	245	49	177	98	0	8.0	3.2
23/3	07	252	118	200	180	0.68	4.0	0.4
22/3	23	662	550	198	180	0.55	8.0	0.4
24/3	14	605	67	190	134	0.23	8.0	4.0
25/3	03	324	111	192	167	0	12.5	0
4/6	22	1975	1301	58	248	-	13.0	7.3
10/6	02	476	402	59	261	0.10	4.5	2.4
11/6	03	230	122	58	251	0	10.0	0
2/7	05	185	471	54	244	0.33	2.0	1.8
5/7	02	223	87	38	159	0	1.0	0.8
20/7	03	230	111	58	237	-	5.5	0
20/7	05	176	34	58	237	-	2.0	0.8
20/7	13	3129	1471	58	182	0	13.5	1.8
20/7	21	2633	2552	58	178	0.10	15.0	7.2
21/7	03	307	177	55	178	0.42	7.5	5.2
21/7	05	147	38	55	178	0.54	3.5	4.2

[illegible]

per cent; for space heating about 65 per cent; and for small industries 25 per cent of the total winter consumption. There are also a few large industries outside the city that release heat but they have not been taken into account.

The other great heat source, sun radiation, was also calculated for the traverses,[14] assuming the built-up area of the city to be circular with a radius of 6400 m (4 miles) (see Fig. 1). A proportion of the solar radiation is, of course, reflected back (albedo) but this was not taken into account. A comparison between the two main sources of energy shows that in winter the sun radiation is only about 25 per cent of the artificial heat energy, but in summertime the opposite is true. The sum of the two components seemed to be constant the year round. This implies that the calculated heat necessary to maintain the heat island is approximately equal to the calculated heat released from the city since in the heat calculations (see page 56) the heat is only received from the upwind half of the city. This is in accordance with Summers' findings.[15] The albedo, varying, especially for the country throughout the year, also has an influence on the size of the heat island and its variation. There is also variation in the absorption of solar radiation throughout the year. Table 11 also gives the pollution concentration during the traverses as given by the smoke sampler at

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[14] Canada, Dept. of Transport, Met. Branch, "Monthly Radiation Summary," Toronto, 1964.

[15] Summers, op.cit.

City Hall and the amount of cloud cover is also given.

As the volume of the heat island is mainly determined by the heat from solar radiation and gas consumption, the amount of air pollution, and the cloud cover, these four elements were correlated to the heat theoretically necessary for the heat island by means of partial correlation coefficients. The heat stored in buildings and streets decreased with time,[16] so it was necessary to eliminate this effect by grouping traverses from the same time of the day. Two groups were used, one consisting of the traverses conducted in winter afternoons, the other in early mornings of winter. The first group contained 7 traverses, the second 11 traverses. The final partial correlation coefficients, when the influence of the other elements (within brackets) is kept constant, was:

Partial correlation coefficients	Day Time (15,16,17,18 hrs)	Night time (04,05,06,07 hrs)
$r_{H\ G\ (S,A,C)}$	-0.20	-0.22
$r_{H\ S\ (G,A,C)}$	0.04	0.12
$r_{H\ C\ (G,S,A)}$	0.52	-0.45
$r_{H\ A\ (G,S,C)}$	0.33	-0.29

where:

H = the heat required to maintain the heat island observed

S = the solar radiation received during the day closest before the traverse

G = the gas consumption of the 24-hour period during which the traverse took place.

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[16] Kratzer, op.cit.

[illegible]

[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]

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[illegible]

A = the concentration of particulate matter during the traverse, measured as soiling index (page 94)

C = cloud cover, average for the hours during which the traverse took place.

The lower rank coefficients are presented in Table 12. The coefficients may seem low, but it has to be borne in mind that the relations that are probably not linear are here approximated by straight lines.

B. Suggested Interpretation of the Partial Correlation Coefficients

The correlation between the heat island energy and the gas consumption, $^{r}H\ G\ (S,A,C)$ is negative both day and night. This may seem somewhat anomolous. The explanation is possibly found in the paucity of observations. As no hourly gas consumption figures were available the figures for the whole day had to be used.

The correlation between the solar radiation and the heat island energy, $^{r}H\ S\ (G,C,A)$ is slight for both day and night. This indicates that the short period variations of the heat island are not immediately determined by the variation of this source.

The correlation between the cloud cover and the heat island energy, $^{r}H\ C\ (G,S,A)$, is the strongest both day and night, but has opposite signs day and night. The most important single factor seemed therefore to be the cloud cover, acting in different ways during the day and the night. The difference in temperature between the city and the country is mainly determined by the magnitude of the terrestrial radiation, a well developed heat island being associated with high values of outgoing radiation. During the day the relative importance of the terrestrial radiation is determined mainly by the amount of solar radiation: the more solar radiation the less important is the terrestrial radiation. Thus increased cloudiness increases the relative importance of the

TABLE 12 - PARTIAL CORRELATION COEFFICIENTS

Coefficient	Day	Night
$r_{H\ G}$	-0.31	-0.14
$r_{H\ S}$	-0.06	0.26
$r_{H\ C}$	0.51	-0.50
$r_{H\ A}$	-0.26	-0.19
$r_{G\ S}$	-0.32	0.30
$r_{G\ C}$	-0.38	0.02
$r_{G\ A}$	0.48	-0.04
$r_{S\ C}$	-0.38	-0.43
$r_{S\ A}$	0.30	0.05
$r_{C\ A}$	-0.79	-0.09
$r_{H\ G\ (S)}$	-0.35	-0.69
$r_{H\ G\ (C)}$	-0.14	-0.15
$r_{H\ G\ (A)}$	-0.22	-0.15
$r_{H\ S\ (C)}$	0.17	0.05
$r_{H\ S\ (A)}$	0.02	0.28
$r_{H\ A\ (C)}$	0.27	-0.27
$r_{G\ C\ (A)}$	0	0
$r_{G\ C\ (S)}$	-0.57	0.17
$r_{G\ S\ (C)}$	-0.53	0.34
$r_{G\ S\ (A)}$	-0.54	0.30
$r_{G\ A\ (C)}$	0.32	-0.03
$r_{S\ A\ (C)}$	0	0.01
$r_{H\ G\ (S\ A)}$	-0.25	-0.26
$r_{H\ C\ (S\ A)}$	0.54	-0.47
$r_{G\ C\ (S\ A)}$	-0.16	0.15
$r_{H\ A\ (G\ C)}$	0.34	-0.28
$r_{H\ S\ (G\ C)}$	0.11	0.11
$r_{S\ A\ (G\ C)}$	0.21	0.02

terrestrial radiation, hereby increasing the difference between city and country temperatures. At night the situation is different as there is no solar radiation. Increased cloudiness at night decreases terrestrial radiation and thereby the heat island.

The correlation between the air pollution concentration and the heat island energy, $^{r}H\ A\ (G,C,S)$, has the same signs as the ones for the cloud cover but air pollutants act in a somewhat different manner as they are closer to the ground. In daytime the particulate matter absorbs the solar radiation and thus heats the air over the city, while at night they radiate more heat away, thereby cooling the air. This is in agreement with Sheppard's results.[17] The influence of air pollution on the heat island seems to be less, both day and night, than that of the cloud cover, but probably is not of more than a minor importance.

However, there is a severe restriction on the reliability of the conclusions: the number of observations (11 and 7) is very small, but since the results seemed possible and so far little information of the relative importance exists in the literature this section was included.

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[17] Sheppard, op. cit., pp. 31-43.

CHAPTER VIII

AN EXAMINATION OF CITY TEMPERATURES

A. Representative Points Along the Temperature Route

The temperature at a specific point can be considered representative when the trends of temperature here are similar to the average trend within the city. It may be that the temperature tends to be 1°C higher or 2°C lower than the average, but the difference is in general maintained during the day.

A technique of determining to what extent a location on a temperature traverse route is representative for its surroundings has been developed by Sundborg.[1] The temperature at a point along the traverse route can be written as:

$$t_{i,j} - t_{.,j} = d_{i,j} + k_i \qquad \text{(VIII.1)}$$

where:

k_i = the average departure from the mean temperature at the point i

$t_{i,j}$ = the temperature at the i:th point, during the j:th traverse

$t_{.,j}$ = the mean temperature for all points during the j:th traverse

$d_{i,j}$ = a random error between the measured temperature $t_{i,j}$ and the expected temperature $t_{.,j} + k_i$ at the i:th point during the j:th traverse

Summing and squaring (VIII.1) for all traverses:

$$\sum_{j=1}^{M} (t_{i,j} - t_{.,j})^2 = M k_i^2 + \sum_{j=1}^{M} d_{i,j}^2 \qquad \text{(VIII.2)}$$

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[1] A. Sundborg, Climatological Studies in Uppsala, Uppsala, 1951, p. 56.

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[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

where:

M = the number of traverses.

If the sum $\sum_{j=1}^{M} d_{i,j}^{2}$ is small the temperature at the point i varies in accordance with the mean temperature for the whole area and thus the point is a good representative for the area.

The city can be divided into subdivisions and the location with the most representative temperature can be chosen for each subdivision. Thus only one temperature measurement need be taken to obtain a valid temperature for each area. No attempt to divide Edmonton into subdivisions was made, but by means of (VIII.2) the points along the traverse route were investigated to learn those locations where the temperature variations most closely approximated those of the mean city temperature. The results of this investigation are shown in Fig. 10. The best point along the route to locate a thermometer in order to get a representative value for the average temperature variation of the city is marked by the letter b (Fig. 10). The locations at which the temperature had least in common with the air over the city were those in the western part of the river valley. Of interest is the variation of the temperature at the Industrial Airport (Fig. 1). Although there are many locations that are more representative, the readings at the airport are considered reasonably representative for the city.

B. The Possibility of Using Temperature Readings from Locations Outside Edmonton to Estimate the Urban Heat Island

One common way to get continuous records of the urban heat island is to use the temperature at one location outside the city in comparison with one obtained inside the city. This technique has been used for

[illegible]

Legend:

Values of $\left[\Sigma d_j^2/(M-1)\right]^{1/2}$

● 0.4° - 0.6°C

● 0.6° - 0.8°C

● 0.8° - 1.0°C

• 1.0° - 1.2°C

• 1.2° - 2.0°C

· >2.0°C

Fig. 10. The degree to which the temperatures at the sampling spots are representative of the mean city temperature. "b" indicates the spot that best represented the variation of the city temperature along the traverse route.

Edmonton by Burrows.[2] He compared both the hourly readings from the International Airport (19 km - 12 mi - to the south of the city) and the readings from Namao Airport (10 km - 5.5 mi - to the north of the city) with the readings from the Industrial Airport (Fig. 1).

For the traverses the maximum temperature difference was calculated and compared with the difference in temperature between the Industrial Airport and Namao Airport. The correlation coefficient was r - 0.38. The corresponding figure using the International Airport was 0.32. These figures suggest that the technique of using readings from relatively distant airports is not very adequate.

An attempt to use the temperature gradient between the two airports outside the city and then find the difference in temperature between the city airport and the appropriate one along the gradient also proved inadequate, in comparison with the found maximum city-country temperature difference from the traverses. The correlation coefficient in this case was r = 0.19.

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[2] W.R. Burrows, "The Heat Island of Edmonton, Alberta," unpublished report to the Dominion Public Weather Office, International Airport, Edmonton, 1964.

[illegible]

CHAPTER IX

ISOTHERM MAPS FOR SELECTED TRAVERSES

Out of the 44 traverses fourteen were chosen to illustrate the previous discussion (Chapter V) on the horizontal temperature distribution over the city. Isotherm maps for these fourteen traverses are presented below together with comments and the following information:

Time for the traverse: The temperature readings of each traverse were reduced to one of the full hours (i.e. 1600, 0300 hrs)

Wind: average wind speed and direction during the traverse, as obtained from the Industrial Airport

Cloudiness: average cloud cover and main type of lower clouds, as received from the Industrial Airport

Relative humidity: average value at the Industrial Airport during the traverse

Snow depth: figures from the Industrial Airport

Precipitation: total value during the traverse as obtained from the Industrial Airport (Tr. = trace)

Air pollution: the two-hourly value recorded at City Hall, measured in COH/1000 foot linear air (see page 94)

Mean temperature: mean temperature of all the 200 points during the traverse

Standard deviation: the standard deviation of the temperature readings from the 200 points during the traverse

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Maximum mixing height: the maximum height calculated according to the heat island theory (see Chapter VI).

Daily heat island energy: the energy required to maintain the measured heat island at the actual hour on a 24-hour basis

Daily gas consumption: the 24-hour consumption figure for the calendar day during which the traverse took place

Daily radiation energy: the amount of radiation energy received at the Industrial Airport multiplied with the horizontal area of the city (assumed circular with a radius of 6400 m (4 mi) (see page 63).

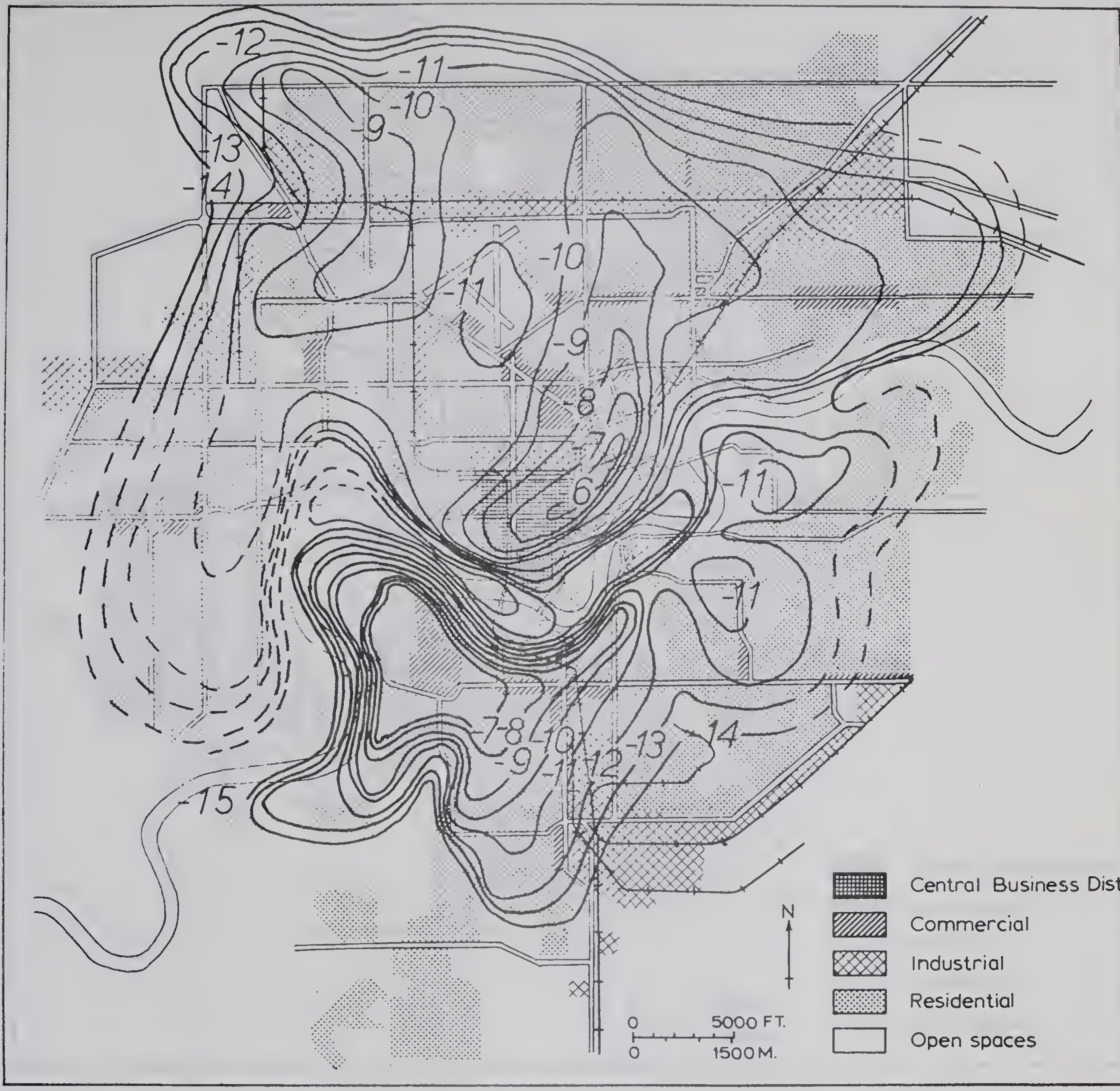

Fig. 11. Isotherm map for January 15, 1964, around 0000 hrs

Wind: SW, 5.5 mi/h	Mean temperature: -11.0°C
Cloudiness: 0	Standard deviation: 2.45°C
Rel. hum.: 73 %	Maximum mixing height: 271 m
Snow depth: 8 cm	Daily heat island energy: 240 10^9 BTU
Precipitation: 0	Daily gas consumption: 159 10^9 BTU
Air pollution: 0.43 COH	Daily radiation energy: 22 10^9 BTU

Of all the traverses this one gave the best developed horizontal temperature pattern. Note how the cold air drainage in the river valley divides the warm air over the city into two halves. The impact on the city temperature by this cold air drainage is by far greatest in the southwestern part of the river valley. The influence of the wind direction on the horizontal temperature distribution is obvious from the tongue of warm air from the city center in northern direction from the city center. Note how the steep gradient in the temperature well approximates the limits of the built-up area of the city.

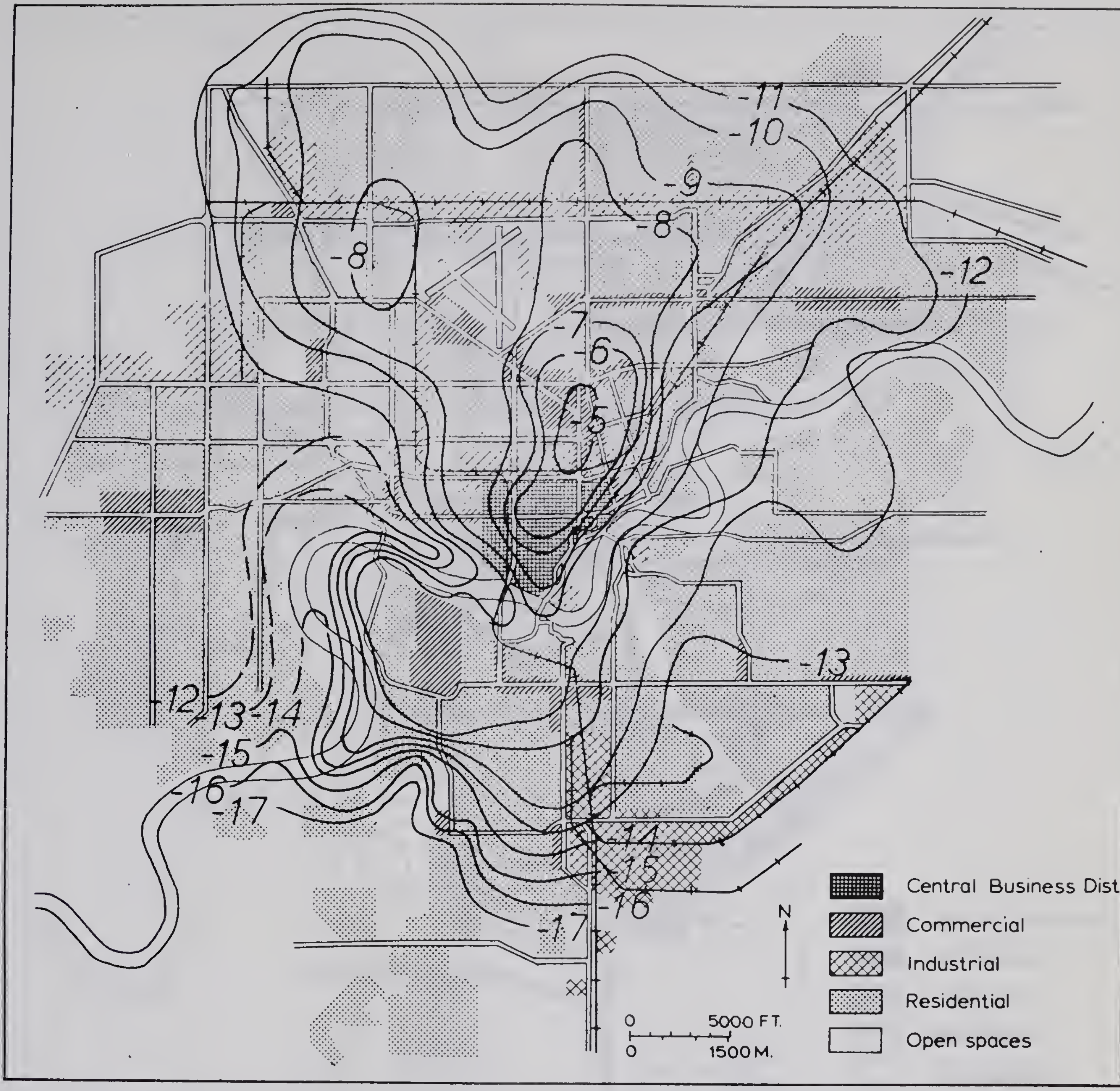

Fig. 12. Isotherm map for February 11, 1964, around 2300 hrs

Wind: S, 8.5 mi/h	Mean temperature: -10.4°C
Cloudiness: AC 1/10	Standard deviation: 2.34°C
Rel.hum.: 71 %	Maximum mixing height: 400 m
Snow depth: 13 cm	Daily heat island energy: 790 10^9BTU
Precipitation: 0	Daily gas consumption: 144 10^9 BTU
Air pollution: 0.10 COH	Daily radiation energy: 36 10^9 BTU

Note how the warm air over the city center is prolonged in a northern direction from the city center. The temperatures along the southern edge are much lower than those along the northern one, indicating that the warm air from the city extends quite a distance down wind from the populated area. The temperature pattern is rather well developed and the depressing effect on the temperature by the airport and adjacent open areas in the northern part of the city is obvious.

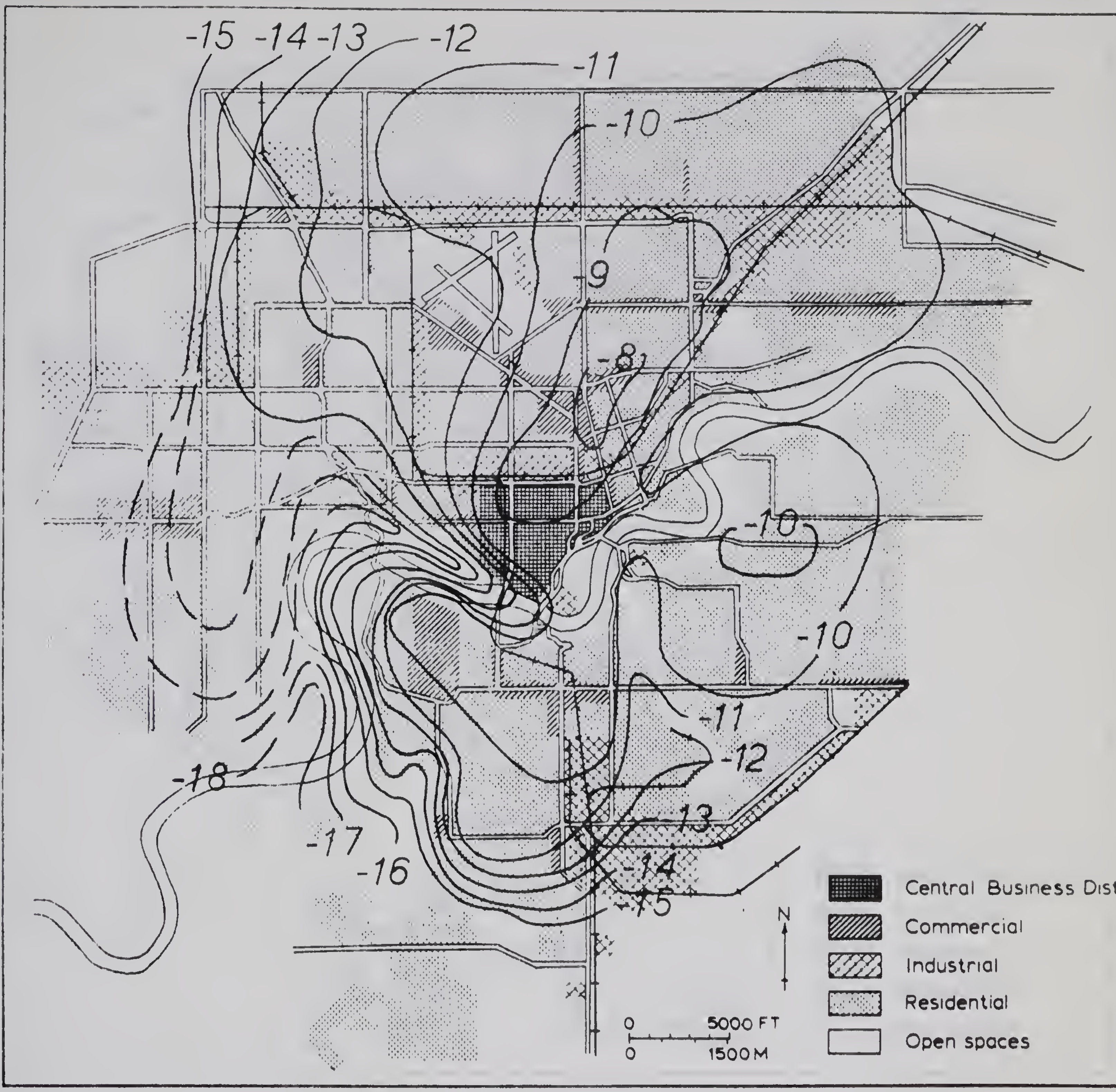

Fig. 13. Isotherm map for February 12, 1964, around 0300 hrs

Wind: S, 6.5 mi/h	Mean temperature: -10.8 °C
Cloudiness: 0	Standard deviation: 2.08°C
Rel. hum. 75 %	Maximum mixing height: 284 m
Snow depth: 13 cm	Daily heat island energy: 253 10^9 BTU
Precipitation: 0	Daily gas consumption: 160 10^9 BTU
Air pollution: 0.33 COH	Daily radiation energy: 36 10^9 BTU

This temperature pattern occurring four hours later than the preceding one (Fig. 12) shows that the center of the city has cooled off, while the surroundings have the same temperature. The river valley is also colder, while the southeastern part of the city is somewhat warmer.

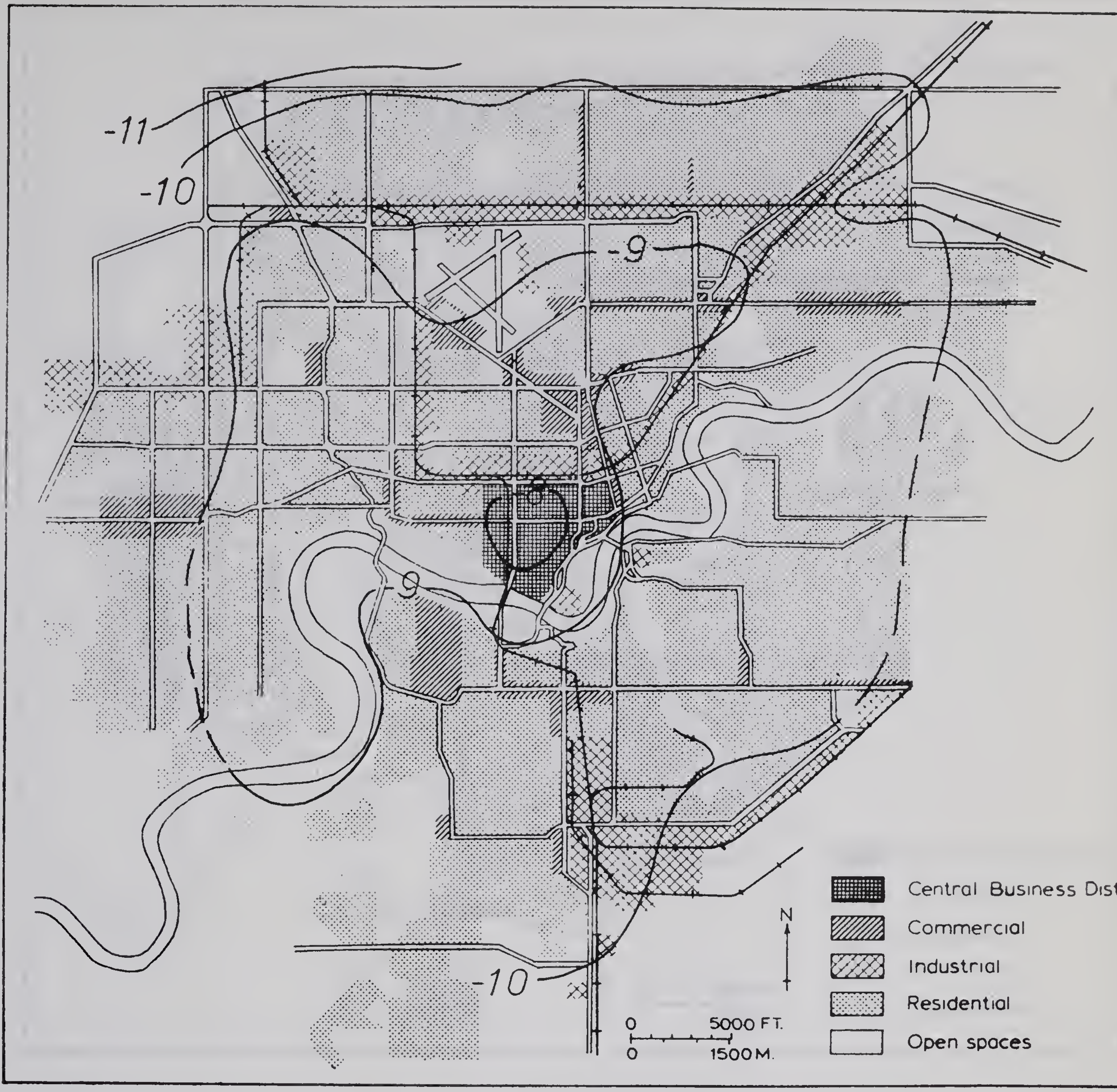

Fig. 14 Isotherm map for March 9, 1964, around 0700 hrs

Wind: SE, 4.0 mi/h	Mean temperature: -9.2°C
Cloudiness: SC 10/10	Standard deviation: 0.49°C
Rel. hum.: 85 %	Maximum mixing height: 129 m
Snow depth: 3 cm	Daily heat island energy: 38 10^9 BTU
Precipitation: Tr.	Daily gas consumption: 155 10^9 BTU
Air pollution: 0	Daily radiation energy: 84 10^9 BTU

In this overcast situation the horizontal temperature pattern is poorly developed in spite of low wind speed. Note the relatively insignificant influence of the river valley on the temperature distribution.

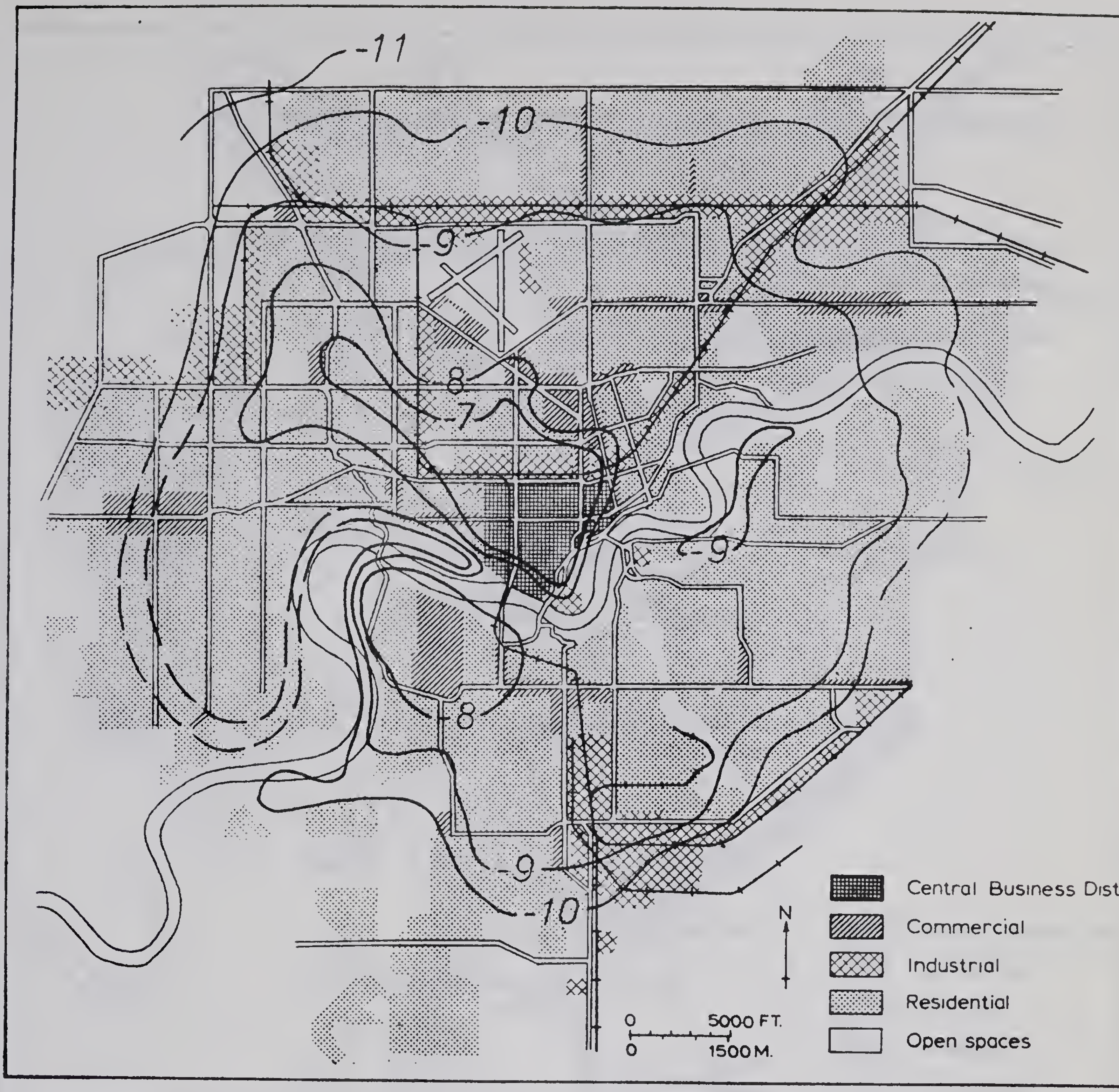

Fig. 15. Isotherm map for March 11, 1964, around 0400 hrs

Wind: SE, 6.5 mi/h	Mean temperature: -8.8°C
Cloudiness: Sc 5/10	Standard deviation: 1.04°C
Rel. hum.: 81 %	Maximum mixing height: 210 m
Snow depth: 8 cm	Daily heat island energy: 142 10^9 BTU
Precipitation: 0	Daily gas consumption: 145 10^9 BTU
Air pollution: 0	Daily radiation energy: 100 10^9 BTU

Note how the center of the warm air is displaced to the northwest of the city center. The warming effect of the city does not extend beyond the limits of the build-up area, even in the wind direction.

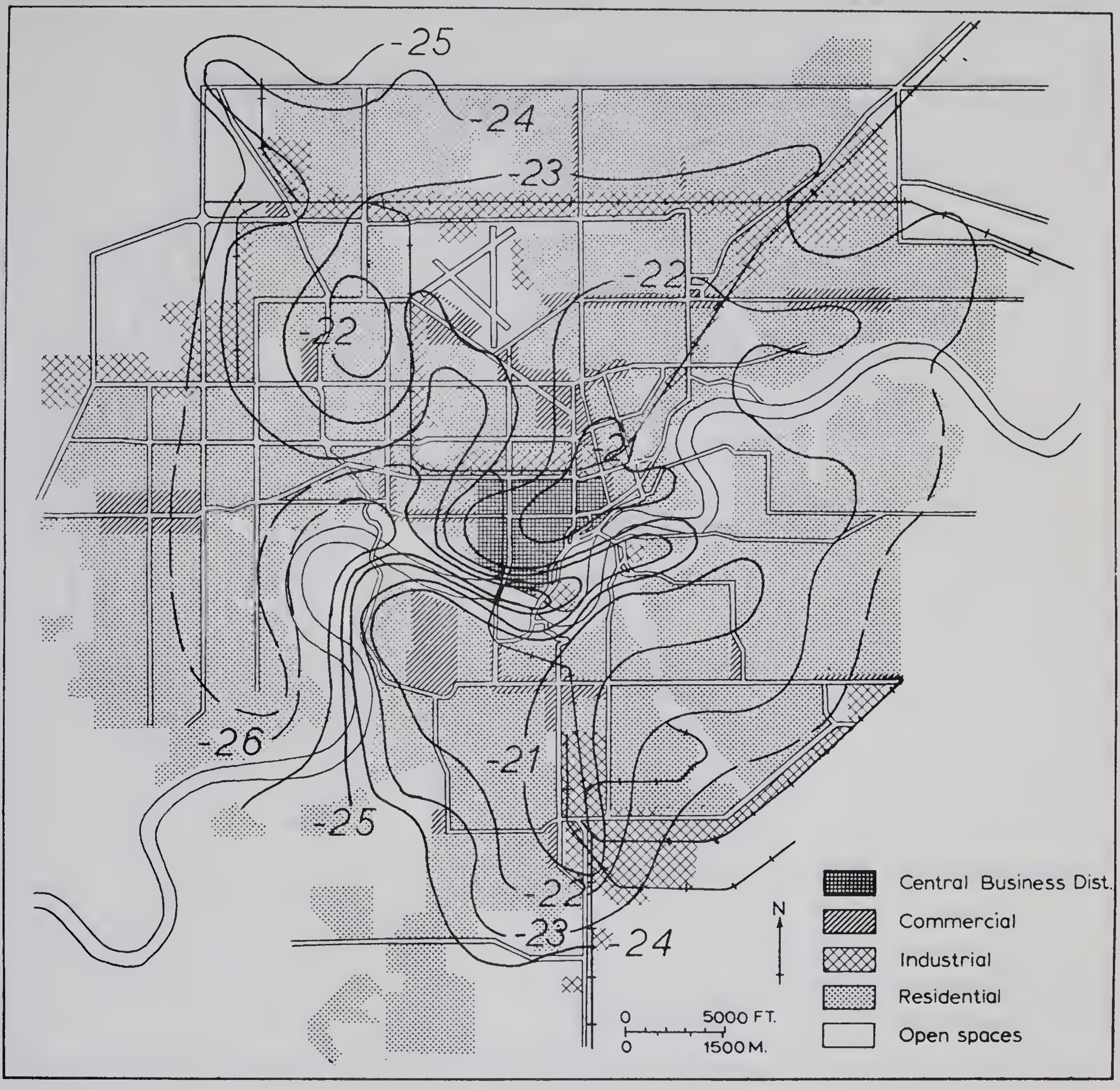

Fig. 16. Isotherm map for March 22, 1964, around 2300 hrs

Wind: N, 8.0 mi/h	Mean temperature: -22.7°C
Cloudiness: 0	Standard deviation: 1.58°C
Rel. hum.: 66 %	Maximum mixing height: 662 m
Snow depth: 8 cm	Daily heat island energy: 550 10^9 BTU
Precipitation: 0	Daily gas consumption: 198 10^9 BTU
Air pollution: 0.55 COH	Daily radiation energy: 180 10^9 BTU

In this situation with rather well developed horizontal temperature pattern note that the main commercial area in the southern part of the city is as warm as the central business district.

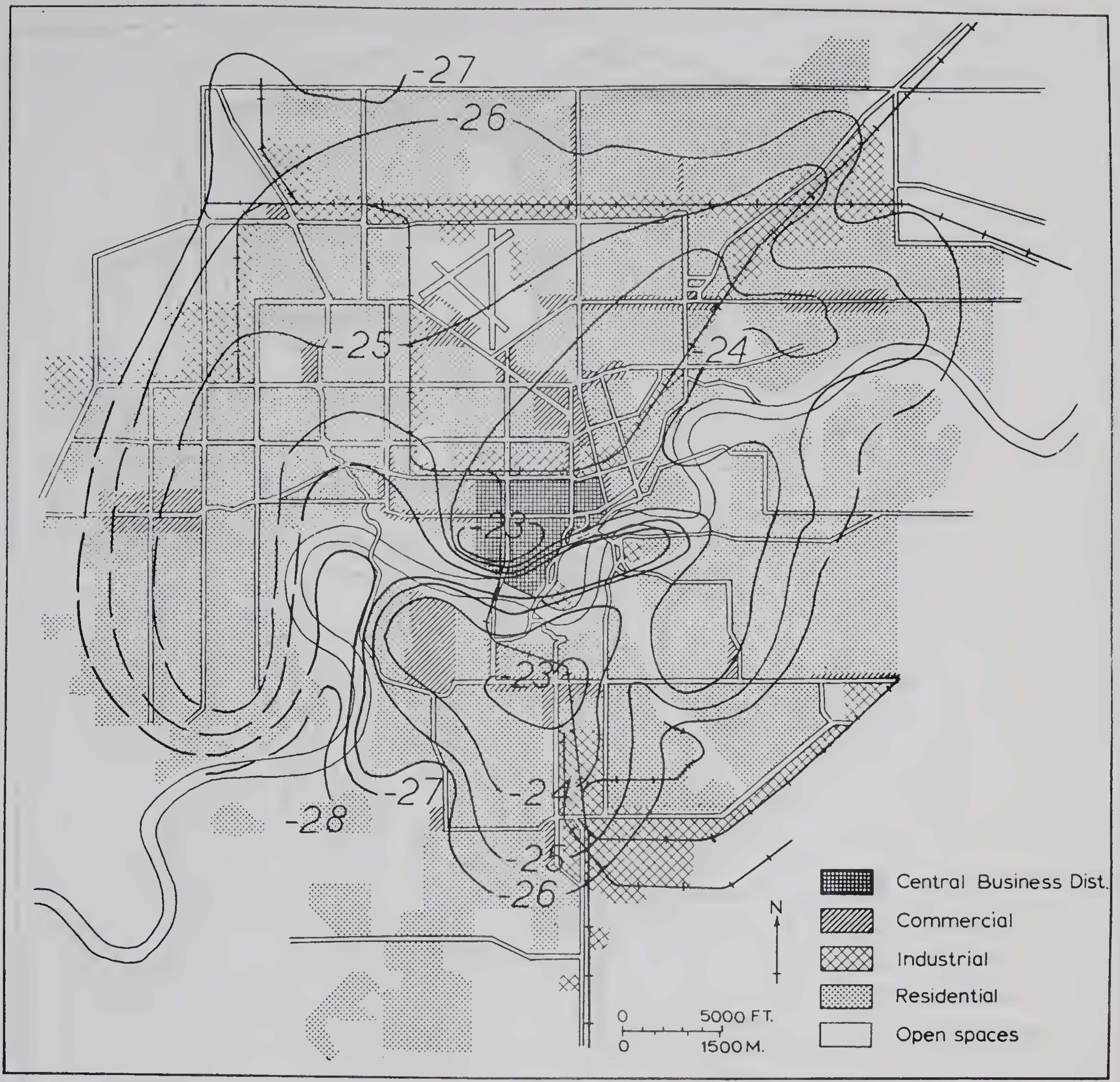

Fig. 17. Isotherm map for March 23, 1964, around 0700 hrs

Wind: N, 4.0 mi/h	Mean temperature: -25.0°C
Cloudiness: 0	Standard deviation: 1.31°C
Rel. hum.: 82 %	Maximum mixing height: 252 m
Snow depth: 3 cm	Daily heat island energy: 118 10^9 BTU
Precipitation: 0	Daily gas consumption: 200 10^9 BTU
Air pollution: 0.68 COH	Daily radiation energy: 180 10^9 BTU

During the eight hours since the preceding traverse no major weather changes had taken place. The city has cooled off at the same rate as its surroundings.

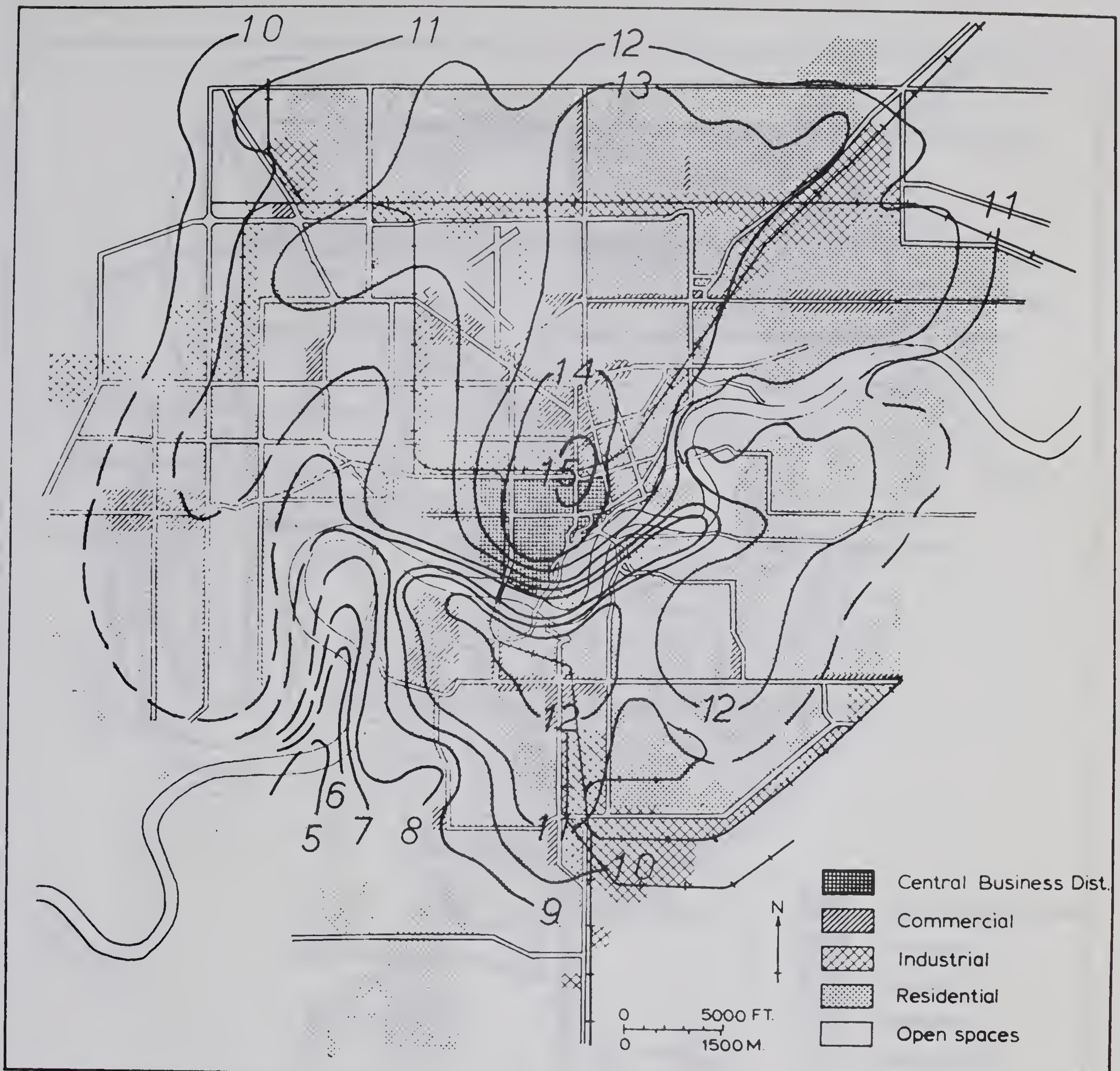

Fig. 18. Isotherm map for June 10, 1964, around 0200 hrs

Wind: S, 4.5 mi/h	Mean temperature: 11.7°C
Cloudiness: Ac, 2/10	Standard deviation: 1.74°C
Rel. hum.: 52 %	Maximum mixing height: 476 m
Snow depth: 0	Daily heat island energy: 402 10^9 BTU
Precipitation: 0	Daily gas consumption: 59 10^9 BTU
Air pollution: 0.10 COH	Daily radiation energy: 261 10^9 BTU

In this well developed summer night temperature pattern note the drainage of cold air that also takes place during summer nights in the river valley.

Fig. 19. Isotherm map for July 2, 1964, around 0500 hrs

Wind: SW, 2.0 mi/h	Mean temperature: 12.1°C
Cloudiness: Cu,Ac, 2/10	Standard deviation: 1.29°C
Rel. hum.: 70 %	Maximum mixing height: 185 m
Snow depth: 0	Daily heat island energy: 471 10^9BTU
Precipitation: 0	Daily gas consumption: 54 10^9 BTU
Air pollution: 0.33 COH	Daily radiation energy: 244 10^9 BTU

The drainage of cold air in the river valley is obvious in this summer night situation with well developed horizontal temperature pattern.

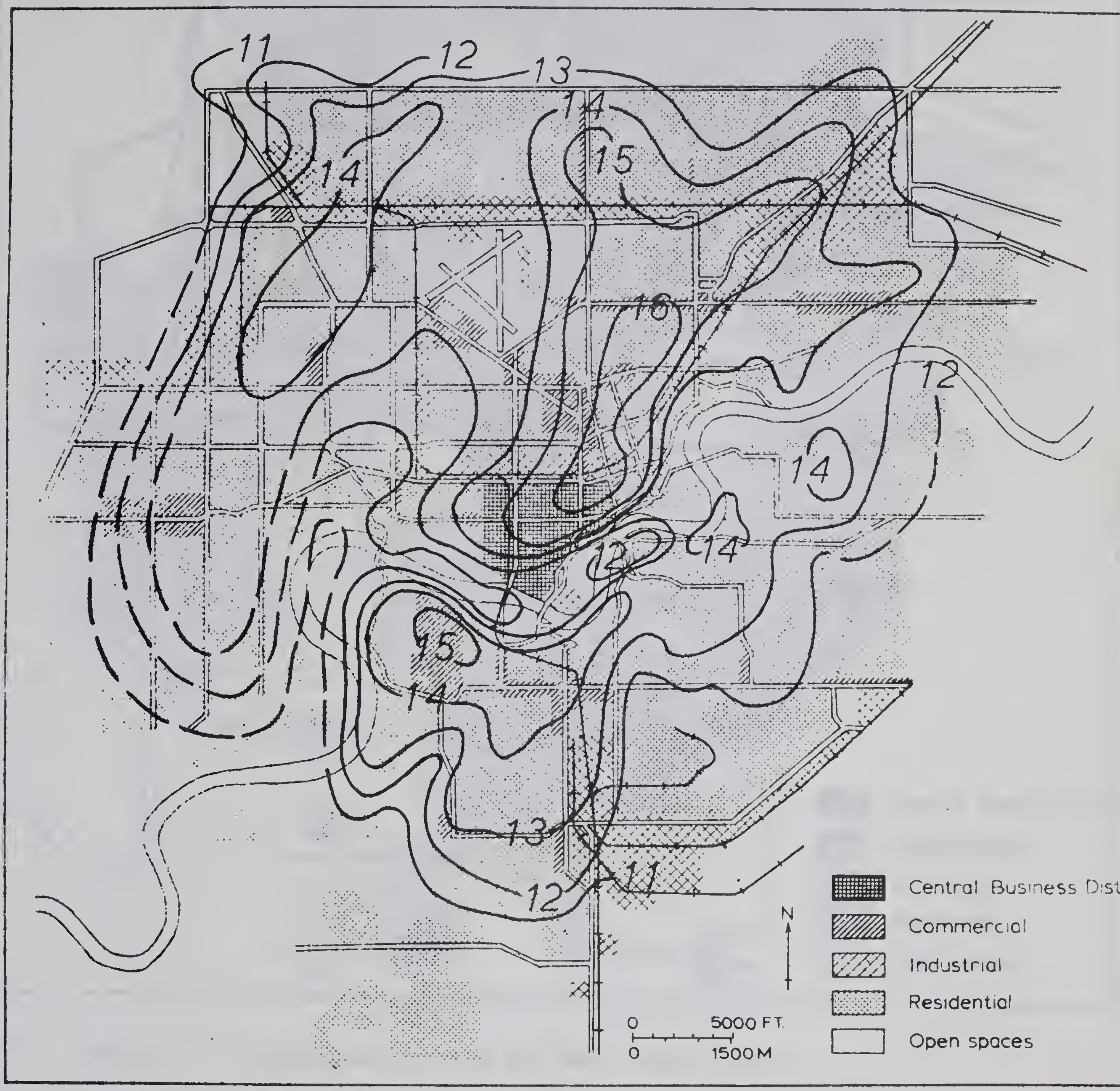

Fig. 20. Isotherm map for July 20, 1964, around 0300 hrs

Wind: SW, 5.5 mi/h	Mean temperature: 13.5°C
Cloudiness: 0	Standard deviation; 1.27°C
Rel. hum.: 75 %	Maximum mixing height: 230 m
Snow depth: 0	Daily heat island energy: 111 10^9 BTU
Precipitation: 0	Daily gas consumption: 58 10^9 BTU
Air pollution: -	Daily radiation energy: 237 10^9 BTU

Note how the ravine in the southern part of the city divides this part into two halves. The airport in the northern part of the city has a similar effect. The displacement of warm air in a northeastern direction from the city center is obvious.

Fig. 21. Isotherm map for July 20, 1964, around 2100 hrs

Wind: E, 15.0 mi/h	Mean temperature: 22.4°C
Cloudiness: Ac, 7/10	Standard deviation: 0.62°C
Rel. hum.: 42 %	Maximum mixing height: 2633 m
Snow depth: 0	Daily heat island energy: 2552 10^9 BTU
Precipitation: 0	Daily gas consumption: 58 10^9 BTU
Air pollution: 0.10 COH	Daily radiation energy: 178 10^9 BTU

This traverse is the first in a series of three made during a summer night. The city effect on the temperature amounts to about four degree Celsius. The cold air drainage in the river valley has not yet divided the horizontal temperature pattern over the city into two halves. The values of the maximum mixing height and the daily heat island energy are probably too high (see page 57).

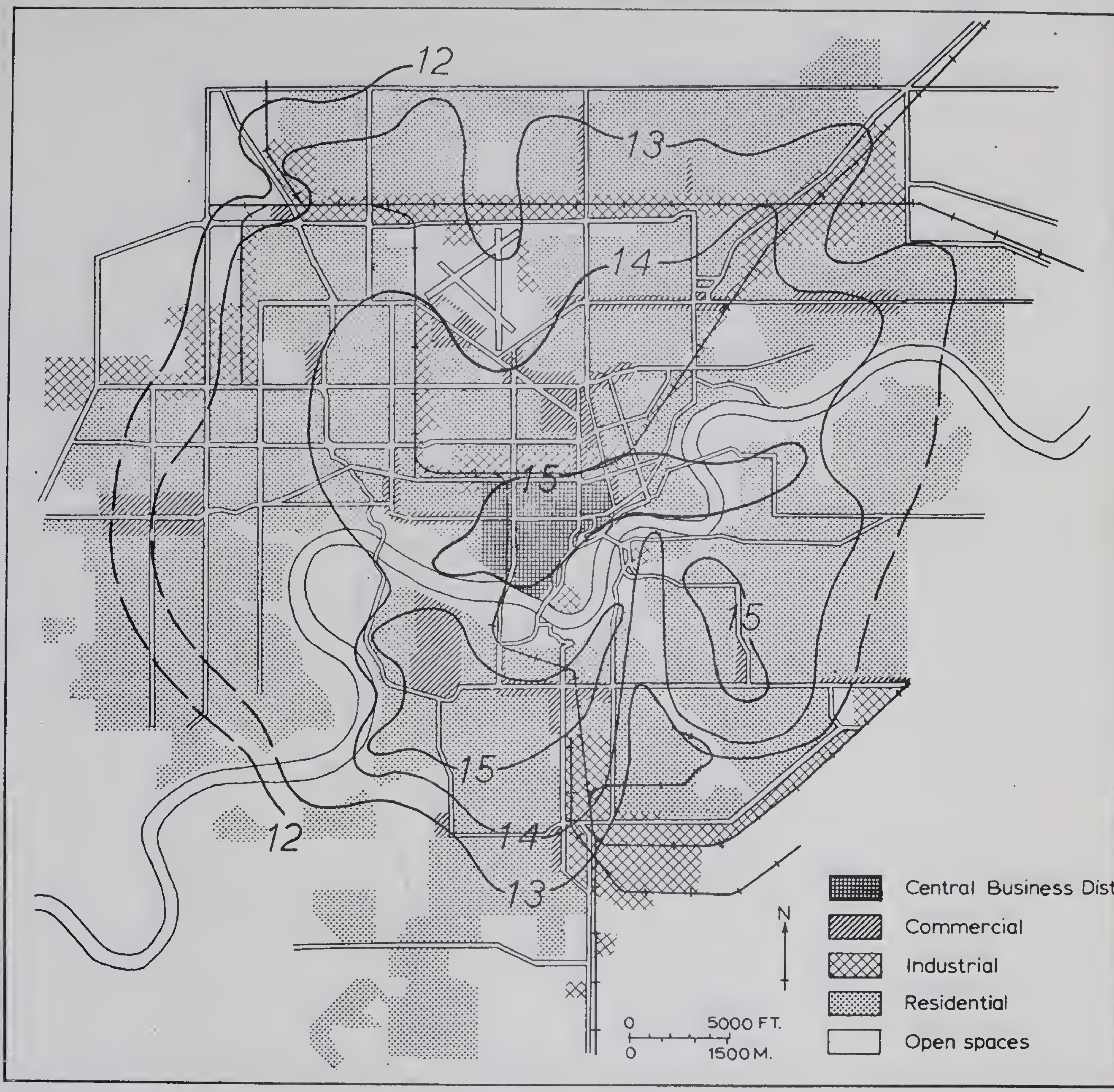

Fig. 22. Isotherm map for July 21, 1964, around 0300 hrs

Wind: NE, 7.5 mi/h	Mean temperature: 14.1°C
Cloudiness: Ac 5/10	Standard deviation: 0.97°C
Rel. hum.: 75 %	Maximum mixing height: 307 m
Snow depth: 0	Daily heat island energy: 177 10^9BTU
Precipitation: 0	Daily gas consumption: 55 10^9 BTU
Air pollution: 0.42 COH	Daily radiation energy: 178 10^9 BTU

This situation occurred six hours after the preceding one. A cooling of 10°C has taken place rather uniformly. However, the drainage of cold air now divides the city temperature pattern into two halves. The drainage of cold air in the ravine in the southern part of the city has also increased.

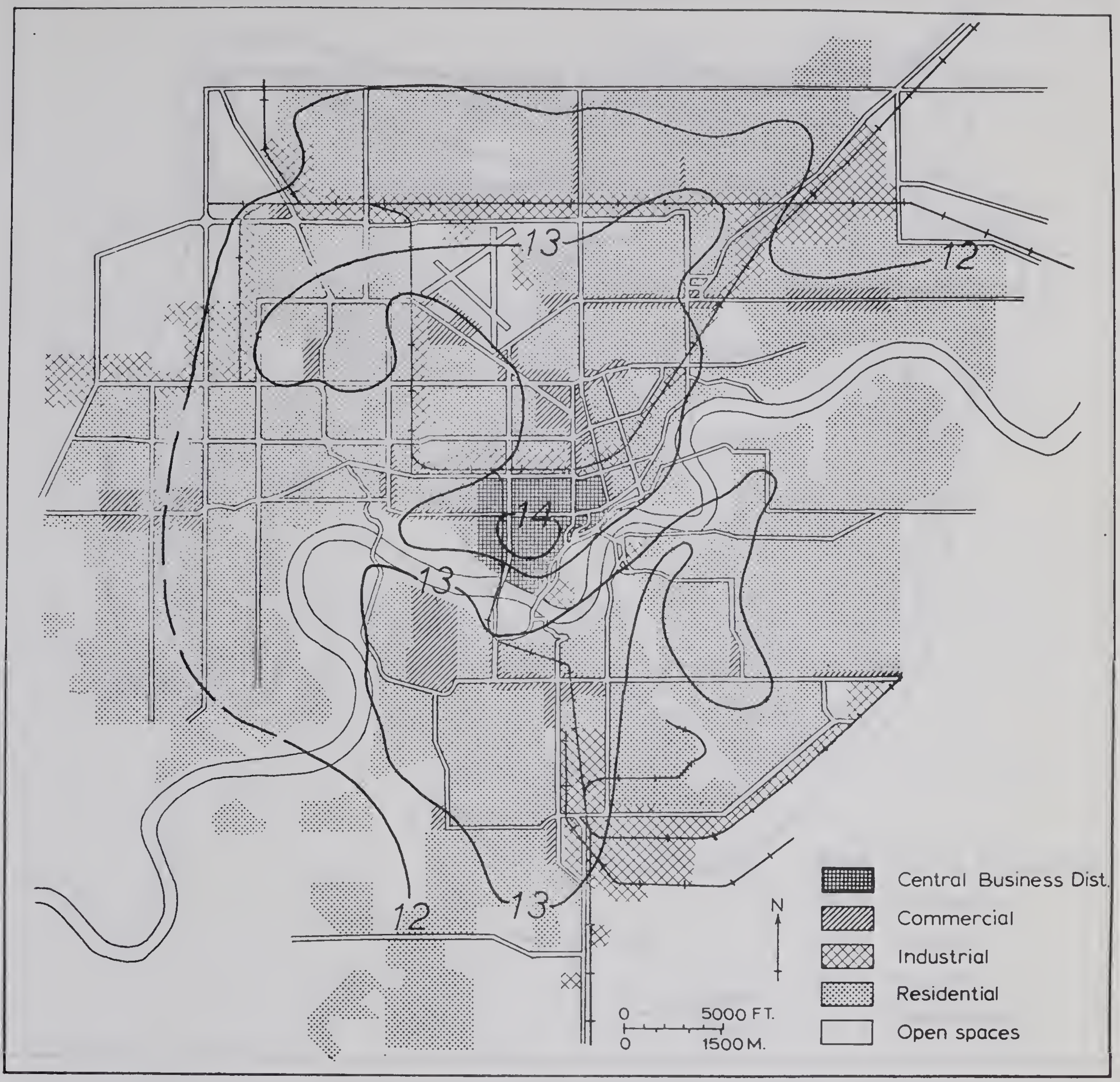

Fig. 23. Isotherm map for July 21, 1964, around 0500 hrs

Wind: NE, 3.5 mi/h	Mean temperature: 12.8°C
Cloudiness: Ac, 4/10	Standard deviation: 0.63 °C
Rel. hum.: 81 %	Maximum mixing height: 147m
Snow depth: 0	Daily heat island energy: 38 10^9BTU
Precipitation: 0	Daily gas consumption: 55 10^9 BTU
Air pollution: 0.54 COH	Daily radiation energy: 178 10^9 BTU

This situation occurred two hours later than the preceding one. Only the warmest part of the city has cooled off and the city-country temperature difference is now only about 2°C compared with 4°C eight hours earlier. The weather situation during these eight hours showed decreasing wind speed and cloud cover.

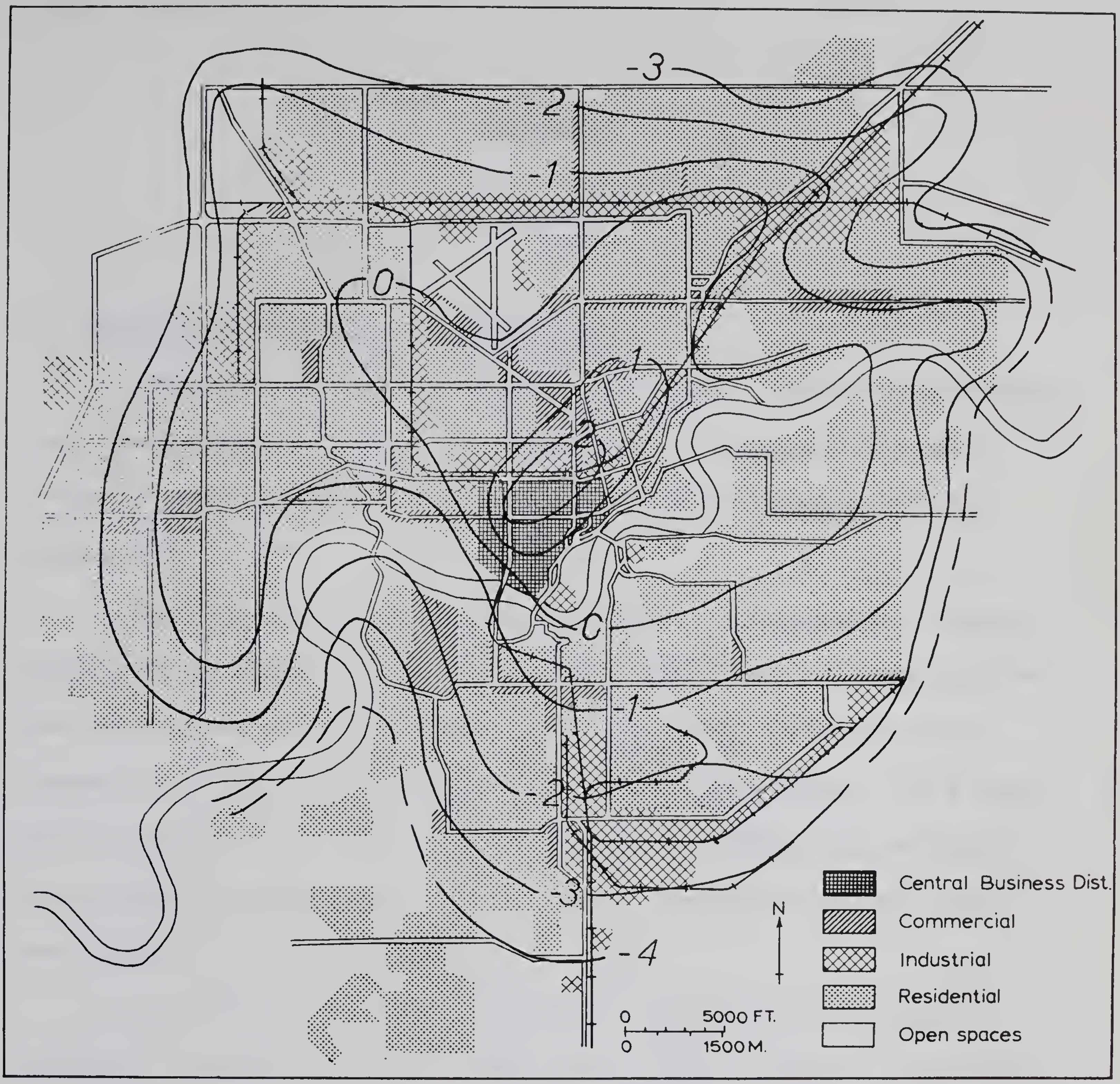

Fig. 24. Isotherm map for November 3, 1964, around 2200 hrs

Wind: S, 4.0 mi/h	Mean temperature: -
Cloudiness: Cu 1/10	Standard deviation: -
Rel. hum.: 64 %	Maximum mixing height: -
Snow depth: 0	Daily heat island energy: -
Precipitation: 0	Daily gas consumption: -
Air pollution: -	Daily radiation energy: -

This separate investigation of the temperatures in the residential districts in Jasper Place (Fig. 1) showed, as expected, no distinct temperature pattern in these areas with the exception of a steep gradient at the boundaries.

CHAPTER X

AIR POLLUTION

A. Definition and Damage of Air Pollution

"Air pollution may be defined as any solid, liquid or gas released into the atmosphere in quantities sufficient to interfere with man's comfort, safety or health, or with the full use and enjoyment of his property."[1]

The term air pollution generally refers to contaminants from man-made sources, but there are natural sources as well. Salt crystals from the oceans cause corrosion. Tree and plant pollen, especially from ragweed, is a problem for people allergic to these products. On a local scale particles from forest fires, volcanoes and duststorms can reduce the sunlight considerably. The most severe pollution problems by far are, however, associated with man's activity.

One recent estimate[2] is that the increased costs for laundry, cleaning of buildings, textile damage and corrosion amount to 42 dollars per person a year. Other effects, more difficult to estimate, are associated with objectionable odours and the reduction of sunlight. Equally difficult to estimate are the negative effects which pollutants

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[1]R.E. Munn, "The Interpretation of Air Pollution Data, with Examples from Vancouver," Canada, Dept. of Transport, Met. Branch, Tec. Cir. Series 3454, Tec. 351, 1961, p. 1.

[2]*Ibid.*, p. 1.

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have upon vegetation and health. During the last decade it has been established that air pollution has an irritating effect on the eyes and the skin, and that decreased sunlight has a negative effect on health in general. "Moreover studies in the United Kingdom and the United States suggest relationships between air pollution and the incidence of lung cancer, chronic bronchitis, emphysema and other respiratory diseases."[3]

B. Classification of Major Air Pollutants

Pollutants may be classified according to:[4]

(a) their physical state, i.e.,aerosol or gas

(b) their chemical nature, i.e., organic or inorganic

(c) their mode of entry, i.e., by direct emission or by being produced in the air by reaction among pollutants or "natural" air constituents. Using this classification, McCormick[5] divides the pollutants into seven groups:

1. Fine particles. (particulate matter). Urban concentration: 50-300 $\mu gm/m^3$. These are usually unburned products of combustion or dust arising from grinding, drying, and similar processes from a host of industrial sources. They are primarily responsible for the soiling of clothing, furniture and other goods, and those smaller than about 1 μ are important in visibility reduction. The organic fraction of the total particulate matter is usually determined by extraction of samples with benzene. This broad separation into inorganic and organic classes is indicative of the source on the particle; in addition, the organic

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[3]M. Katz, "Air Pollution as a Canadian Regional Problem," A background paper for the Regional Development I (general part) of the "Resources for Tomorrow" Conference, 1962, p. 2.

[4]R.A. McCormick, "Air Pollution - Some Meteorological Aspects," Weatherwise, Vol. 15, No. 6, 1962, pp. 229-238.

[5]Ibid., pp. 230-232.

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fraction contains a number of compounds that are of particular health interest because they are potential carcinogens.

2. Sulfur dioxide. Urban concentration 0-30 ppm.[6] The most common source for this gas is the burning of fossil fuels. The gas has an irritating effect on human beings and a corrosive effect on metals and buildings.

3. Carbon monoxide. Urban concentration 5-10 ppm. This gas is formed by the incomplete combustion of any material containing carbon, but the most common source appears to be automobile exhuasts. In high concentrations ($>$100 ppm) the gas has toxic properties.

4. Products of photochemical reactions. Urban concentration 0.1-2 ppm. "Many of the gases and particulates remain chemically inert during their residence in the atmosphere. However the major cause of the Los Angeles smog is the photochemical reaction, which is triggered by sunlight. The basic ingredients are oxides of nitrogen formed mainly by the high temperature combustion of gasoline and petroleum hydrocarbons. This type of air pollution '...is characteristic of any modern city whose economy is geared to the use of petroleum fuels.'[7] When acted upon by sunlight, the mixture produces ozone and other oxidants which are irritating to plants and animals."[8]

5. Total oxidants and ozone. The concept of "total oxidant" represents an attempt to characterize quantitatively the oxidation potential of a polluted atmosphere - particularly that of "photo-

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[6] parts per million by volume

[7] A.J. Haagen-Smit, "The Application of Phenophtalin Reagents to Atmospheric Oxidant Analyses," Advances in Geophysics, Vol. 6, 1959, pp. 1-18.

[8] Munn, op.cit., p. 2.

chemical smog" type. It is usually measured in terms of the amount of iodine released by the exposure of a stream of contaminated air to a buffered neutral potassium iodide reagent[9], though other procedures are also used. Ozone, one of the compounds included in "total oxidants", is known as an agent for rubber cracking. A total oxidant concentration of 0.15 ppm for one hour is set in California as the "adverse level" defined as the "level at which there will be sensory irritation, damage to vegetation, reduction in visibility or similar effects."[10,11]

6. Radioactive pollutants. These are generally derived from nuclear device tests and as far as admitted represent no problem yet.

7. Other pollutants. Although important, carbon dioxide and aeroallergens are not considered to be in quite the same class of problem as those in the above list.

C. The Measurement of Air Pollution

There are several different methods of measuring the concentration of contaminants in the atmosphere. The most common ones are commented on below.

1. The Dustfall Can. This simple instrument consists of an open can exposed to the air. Generally once per month the catch is weighed and analyzed.

2. Chemical methods. By letting contaminated air bubbles through certain solutions during given time periods it is possible to

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[9] M.L. Weisburd (Ed.), Air Pollution Control Field Operations Manual, U.S. Public Health Service Publications, No. 937, 1962.

[10] J.R. Goldsmith, "Some Implications of Ambient Air Quality Standards," Archives of Environmental Health, Vol. 4, 1962, p. 151.

[11] McCormick, op.cit., p. 232.

determine the concentrations of sulfur dioxide, ozone, hydrogen sulphide, carbon monoxide, hydrocarbons and aldehydes.[12]

3. Visibility reduction. Visibility generally decreases with increased air pollution. Holzworth,[13] working in the United States, found that the visibility generally decreased in cities as population increased. When air pollution control was enforced in the several cities studied, however, visibility increased. This relationship between air pollution and visibility, then, can be used to indicate pollution levels for earlier periods when no direct measurements of pollution were made.

4. Reduction of sunlight. Two Pyrheliometers (direct solar radiation intensity recorders), one located in the city, the other in a nearby rural environment, provided the data, which when compared gave the reduction of sunlight caused by the pollutants over the city. This method has been used in Toronto.[14] By measuring the turbidity of the air at different heights over a city, McCormick and Baulch[15] were able to get important information about the vertical distribution of pollutants. The instrument used, a turbidity meter, was recommended by the authors, but can be used only during clear days.

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[12] C.A. Gosline, L.L. Falk and E.N. Helmers, Air Pollution Handbook, Section 5, New York, 1956.

[13] G.C. Holzworth, "Some Effects of Air Pollution on Visibility in and Near Cities," Symposium Air Over Cities, SEC Technical Report A62-5, 1961, pp. 69-87.

[14] J.H. Emslie, "The Reduction of Solar Radiation by Atmospheric Pollution at Toronto," Canada, Dept. of Transport, Met. Branch, Tec. Cir. Series 4094, Tec. 535, 1964.

[15] R.A. McCormick and D.M. Baulch, "The Variation with Height of the Dust Loading Over a City as Determined from the Atmospheric Turbidity," J. Air Poll. Control Assoc., Vol. 12, No. 10, 1962, pp. 492-496.

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5. High Volume Sampler. This instrument can be described as a large household vacuum cleaner. Since the air stream flow is constant day by day, the amount for different days can be compared. Each catch is generally analyzed chemically.

6. Dust Counters. A sample of air is drawn through a tapered metal tube and allowed to impinge upon a glass slide covered with a viscous substance. The number of particles on the slide is then counted through a microscope. This kind of instrument has been used successfully in Germany, where dust measuring traverses have given the first maps of the horizontal distribution of air pollution over a city.[16,17]

7. The Electrical Conductivity of the Air. Since the conductivity of the air is determined by the amount of small particles and ions, the conductivity can be used as a measure of the concentration of pollutants in the air. This method has been used by Wait[18] in the U.S.A. and by Stehberger[19] in Germany.

8. The A.I.S.I. Smoke Sampler. As the records from an instrument of this kind have been used in the author's investigations, it will be described more fully below.

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[16] G. Schmidt, "Zur Nutzbarmachung staubklimatischer Untersuchungen für die städtebauliche Praxis," Beitrag der Deutche Wetterdienst, U.S. Zone, Vol. 38, 1952, pp. 201-205.

[17] E. Flach, "Über ortsteste und bewegliche Messungen mit dem Scholzschen Kernzähler und dem Zeiss-schen Freiluftkonimeter," Zeits. f. Met., Band 6, 1952, pp. 96-112.

[18] G.R. Wait, "Some Experiments Relating to the Electrical Conductivity of the Atmosphere," Journ. of the Washington Acad. of Science, Vol. 36, No. 10, 1946, pp. 321-343.

[19] K.H. Stehberger, "Eine 'elektrische Nase' zur kontinuerlichen Beobachtung des atmosphärischen Aerosols," Beitrag der Deutche Wetterdienst, U.S. Zone, No. 12, 1950, pp. 171-176.

D. The A.I.S.I. Sampler

In this sampler, developed by the American Iron and Steel Institute (A.I.S.I.), air is drawn through a strip of filter paper. The optical density of the resulting spot (particulate deposits) on the filter paper is determined by measuring the light transmission through the spot. The method is described in full elsewhere.[20] For comparison with other samplers the optical density is converted to a unit scale called the COH unit, defined as follows:

$$1 \text{ COH unit} = 100 \times \text{O.D.} \qquad (X.1)$$

where:

O.D. = the optical density

COH is an abbreviation for "coefficient of haze." Another expression for the COH unit is "the soiling index." This value is still dependent on the volume of air drawn through the filter paper, but is generally standardized by the use of 1000 feet linear air.

$$\text{COH units per 1000 ft linear air} = \frac{\text{O.D.} \times 10^5}{L} \qquad (X.2)$$

where:

L = the quantity of air sampled expressed in linear feet.

The optical density (O.D.) is calculated as follows:

$$\text{O.D.} = \log_{10} \frac{I_0}{I} \qquad (X.3)$$

where:

I_0 = the intensity of transmitted light through the clean paper

I = the intensity of transmitted light through the soiled paper

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[20] J.C. Park, D.M. Keagy and W.W. Stalker, "Developments in the Use of the A.I.S.I. Automatic Smoke Sampler," J. Air Poll. Control Assoc., Vol. 10, No. 4, 1960, pp. 303-306.

The quantity of air sampled (L) in linear feet can be expressed as:

$$L = \frac{\theta \times \bar{q}}{A} \qquad (X.4)$$

where:

θ = the sampling time in minutes

$\bar{q}$ = the average flow rate for the sampling period in cubic feet per minute

A = the area of the sampled spot in square feet

For the A.I.S.I. sampler whose records were used in the author's investigation; the following values are valid:

θ = 120 minutes

A = 0.0054 ft^2 (diameter of the spot = 1 inch)

$\bar{q}$ = 0.211 cfm

Substituting these values in (X.2) gives:

$$COH/1000\ ft = O.D. \times 100 \times \frac{1000 \times 0.0054}{0.211 \times 120}$$

or:

$$O.D. \times 100 = COH/1000\ ft \times 4.7 \qquad (X.5)$$

<u>Calibration of smoke density.</u> Sullivan[21] found that the best expression for the calculation of smoke density from smoke stains of one-inch diameter was as follows:

$$M' = \frac{a\ (D. \times 100)^b}{V^{0.67}} \qquad (X.6)$$

where:

M' = mass of particles with diameter less than 10 microns in micrograms per m^3

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[21] J.L. Sullivan, "The Calibration of Smoke Density," Presented at the 55th Annual Meeting of Air Pollution Control Association, Chicago, 1962.

$D.$ = optical density by reflection

$a = 33.0$

$b = 1.24$

The optical density by reflection was arrived at by measuring the decrease of intensity of a light beam reflected off the smoke spot. This way of measuring the density of the smoke spot was found to be more accurate than the earlier method, where the extinction of the light beam was measured after the beam had passed through the smoke spot (equation X.3). However, the optical density (O.D.) by transmission is closely related to the optical density by reflectance (D.) for the smoke samplers Sullivan used. This connection can be written:

$$D. = O.D. \times \frac{43}{44} \qquad (X.7)$$

For a two-hour period which was used in the author's investigations the volume (V) that passed through the instrument used was:

$$V = \theta \times \bar{q} = 120 \times 0.211 = 25.32$$

Substitution of this value and (X.7) into (X.6) gives:

$$M' = \frac{33.0(O.D. \times 43/44 \times 100)^{1.24}}{25.32^{0.67}} = 3.76\ (O.D. \times 100 \times 43/44)^{1.24} \qquad (X.8)$$

Substitution of (X.5) gives:

$$M' = 3.76\ \left(COH/1000\ ft \times \frac{0.211 \times 120 \times 43}{1000 \times 0.0054 \times 44}\right)^{1.24} = 25.02(COH/1000\ ft)^{1.24} \qquad (X.9)$$

The mass (M') refers only to the fraction of particles with a diameter of less than 10 microns, as the particles larger than 10 microns were filtered away. The fraction of small particles varied between 60 and 80 per cent of the total mass of particles. As there was no filter on the sampler used in the author's investigation Eqn (X.9) has to be altered to involve all particles in the investigation. This was done by

assuming an average efficiency of the filter of 70 per cent, thus

Eqn (X.9) becomes:

$$M = \frac{100}{70} \times 25.02(\text{COH}/1000\ \text{ft})^{1.24} = 35.74(\text{COH}/1000\ \text{ft})^{1.24} \quad (\text{X.10})$$

where:

M = total mass of particules in micrograms per m^3.

CHAPTER XI

EMISSION, DEPOSITION AND MEASURED CONCENTRATION OF POLLUTANTS IN EDMONTON

The concentration of air pollution is determined by:

(a) the rate of emission

(b) the rate of diffusion

(c) the rate of deposition

A. Emission

In recent years source surveys have been conducted for several cities. During the summer of 1964 a detailed source survey was made for Edmonton by the Government of the Province of Alberta, Department of Public Health, Division of Sanitary Engineering.[1] Questionnaires were sent to some 210 industries in and around the city. In these the industries were asked to tell:

(a) their finished product and raw material

(b) the amount of material used in the production

(c) air pollution cleansing apparatus used

(d) the amount of waste and the method of its disposal

(e) if possible, the amount of pollutants released into the atmosphere.

As the industries generally did not know their rate and kind of pollutant emission these were calculated from known values for the different kinds of production. The emission from domestic and commercial waste

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[1] J.J. Rolston, A Study of Air Pollution Sources and their Significance in Edmonton, Alberta, Govt. of the Province of Alberta, Dept. of Public Health, Div. of Sanitary Engineering, 1964.

burning was estimated from samples and the emission from traffic was calculated from the gasoline consumed in the city. The results of the survey of sources are shown in Table 13. As can be seen in the table, the emission of particulate matter from the category "fuel usage" is negligible. This category in general is composed of the emissions from the heating of buildings and domestic needs. Since natural gas generally is used for these purposes, the emission of particulate matter is confined to a limited number of industries, from disposal of garbage and from the traffic. Burning of natural gas does not produce particulate matter. In general, thousands of buildings create a large number of small sources emitting particulate matter. This fact generally makes the use of mathematical models for the calculation of the concentration of particulate matter very elaborate and difficult.

The pollutants in a city need not come only from the city itself. In areas with several large industrial cities, the influence from other cities can be considerable. This was for instance the case in Leicester, England.[2] There are only a few industries in Edmonton's vicinity (in Fort Saskatchewan, 28 km - 45 mi - to the northeast and in Clover Bar, 12 km - 19 mi - to the east of the city), that are able to influence the pollution level in the city.

B. Deposition

According to Pasquill,[3] deposition of airborne material on the ground may occur in three ways:

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[2] Dept. of Scientific and Industrial Research, London, Atmospheric Pollution in Leicester, H.M.S.O., London, 1945.

[3] F. Pasquill, Atmospheric Diffusion, London, 1962, p. 226.

[illegible]

TABLE 13 - THE EMISSION OF ATMOSPHERIC POLLUTANTS IN EDMONTON 1964

Compound	Per cent of total emission				Total Emission	
	Industrial emission	Disposal of garbage and refuse	Fuel Usage	Motor Vehicles	tons/year	tons/day
Total hydro-carbons	57.3	20.8	2.8	19.0	88,693	242
Sulfur di-oxide	94.0	n	n	6.0	4,849	13
Particulate matter	80.4	17.8	n	1.8	10,812	30
Carbon mon-oxide	27.6	24.6	n	47.8	288,599	791
Oxides of nitrogen	11.1	0.6	50.0	38.3	15,489	42
Aldehydes	1.8	77.3	16.3	4.6	4,697	13
Ammonia	75.5	18.3	0.7	5.5	1,236	3
Acetylene		na	n	n	2	n
Phenol	0.4	99.6	n	n	456	1
Other organic		na	n	n	1,742	5

n - negligible
na - not available

Source: J.J. Rolston, A Study of Air Pollution Sources and their Significance in Edmonton, Alberta, Govt. of the Province of Alberta, Dept. of Public Health, Div. of Sanitary Engineering, 1964.

(a) general sedimentation of particles or droplets

(b) retention at the ground surface by processes such as impaction and absorption, with subsequent downward turbulent transport to the sink thereby formed

(c) washout of the material in association with rain or other forms of precipitation.

Pasquill[4] gave some elaborate expressions for these kinds of deposition, of which the simplest one came from Meetham.[5,6] Meetham assumed that the reduction of material in the air as a result of deposition follows an exponential law viz:

$$1^1/m^1 = \exp(-\bar{T}/t) \qquad \text{(XI.1)}$$

where:

1^1 = the rate of loss by pollutants blowing out to the sea

m^1 = the total rate of emission

$\bar{T}$ = the average time the material travels over land

t = the time constant.

Using this expression Meetham found the average "life time" for smoke to be 28 hours and for sulfur dioxide 8 3/4 hours for average wind conditions. "Life time" is defined as twice the time required to reach half of the original concentration. The figure for sulfur dioxide has been used by Turner in his study of the sulfur dioxide concentration over Nashville, Tennessee, U.S.A.[7] As the figure for smoke (particulate matter) is rather high, the author will later assume that the deposition of particulate matter is negligible in the short time, maximum three hours, it takes for the pollutants to reach City Hall, Edmonton, from the outskirts of the city.

Wash-out by Precipitation

There are several estimates of the wash-out effect by precipi-

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[4] Ibid., pp. 226-239.

[5] A.R. Meetham, "Natural Removal of Pollution from the Atmosphere," Quart. Journ. R. Met. Soc., Vol. 76, 1950, p. 359.

[6] Idem., "Natural Removal of Atmospheric Pollution During Fog," Quart.Journ. R.Met. Soc., Vol. 80, 1954, p. 96.

[7] B.D. Turner, "A Diffusion Model for an Urban Area," J. Appl. Met., Vol. 3, No. 1, 1964, pp. 83-91.

tation. The amount of fallout is dependent upon:[8]

(a) the size of the droplets

(b) the rate of fall

(c) the duration of the precipitation period.

The meteorological conditions associated with precipitation are generally those which provide higher winds and thus better ventilation. Therefore, lower pollution level may accompany precipitation regardless of whether the rain or wash-out was responsible for a decrease.[9] Munn gave as high a figure as 90 per cent as possible wash-out effect.[10] The same figure was given by Pemberton for wettable material.[11] In Leicester, the correlation between pollution concentration and precipitation was found to be -0.5.[12] For Paris, Grisollet found the effect of precipitation as a cleaner of the air significant. Especially important was the effect during the first hour of the rainfall.[13] In the author's investigation, no consideration will be paid to the precipitation effect, partly because the effect probably is almost the same for all directions, and partly because the amount of precipitation is very little during the winter months.

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[8] International Joint Commission, Pollution of the Atmosphere in the Detroit River Area, Ottawa, 1960, p. 193.

[9] Ibid., p. 135.

[10] R.E. Munn, "The Interpretation of Air Pollution Data, with Examples from Vancouver," Canada, Dept. of Transport, Met. Branch, Tec. Cir. Series 3454, Tec.351, 1961, p. 5.

[11] C.S. Pemberton, "Scavenging Action of Rain on Non-wettable Particulate Matter Suspended in the Atmosphere," Int.J.Air Poll., Vol.3, 1961.

[12] Dept. of Scientific and Industrial Research, op.cit.

[13] H. Grisollet and J. Pelletier, "La pollution atmosphérique au centre de Paris et ses relations avec quelques facteurs climatologiques," La météorologie, juillet-septembre, 1957, p.402.

C. Variation of the Soiling Index in Edmonton

Time Variation of the Soiling Index in Edmonton. In 1959, an A.I.S.I. sampler was installed by the Department of Health on the seventh floor of the Edmonton City Hall (Fig. 1) which is located in the central business district of the city.

In 1962, the instrument was moved to the Administration Building (Fig. 1), located just south of the central business district, where it was operating on the fourth floor. The following year it was transferred back to City Hall.

Since August 1964, there have been six A.I.S.I. samplers operating in the city, the location of which, together with the location of other samplers, is shown in Fig. 25.

For 1963 the average soiling index for the sampler at City Hall was 0.37.[14] Mean values for other Canadian cities, given in Table 14, show that this index is relatively low.

TABLE 14 - MEAN SMOKE CONCENTRATION FOR SOME CANADIAN CITIES

	Mean Yearly Soiling Index
Ottawa, commercial district	2.20
Windsor	1.80
Winnipeg, central business district	0.84
Winnipeg, residential district	0.38
Vancouver, central business district	1.11
Harrow, Ontario	0.60
Montreal, central business district*	2.08

*P.W. Summers, "Urban Ventilation in Montreal," Smokeless Air, No. 128, 1963, p. 119 (fig. for Montreal only)

Source: M. Katz, "Air Pollution in Canada - Current Status Report, Amer. Journ. of Public Health Assoc.,Vol.3,No.2,1963,p.176.

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[14] D.T. Keenan, Air Pollution in Edmonton, 1963, unpublished report to Govt. of Alberta, Dept. of Public Health, 1964.

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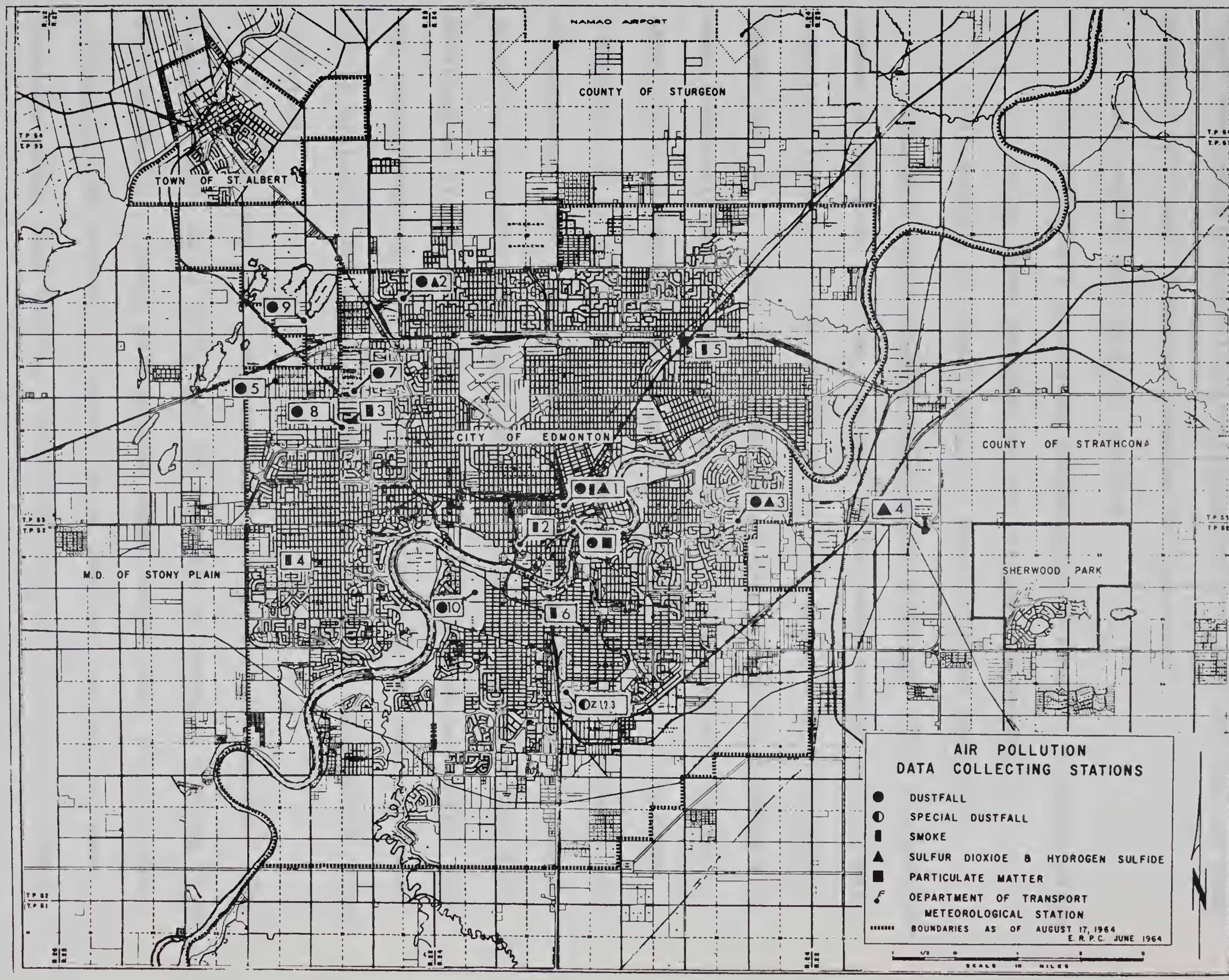

Fig. 25. The locations of air pollution samplers in Edmonton, 1964

There are probably several contributing factors that make the air over Edmonton so clean. Suggested reasons for this are:

(a) natural gas used for heating;

(b) low relief preventing trapping of surface air in depressions as is often the case in for instance Los Angeles;

(c) absence of large industrial centers in the vicinity.

The Daily Concentration of Smoke and Nitrogen. Fig. 26 shows the number of two-hour readings recorded by the smoke sampler at City Hall, Edmonton, 1963, which during the 24-hour period had a soiling index larger than 0.9. While most other cities have a dominating maximum of smoke concentration at about eight o'clock in the morning, the daily smoke cycle at Edmonton has no such a morning maximum. The maximum concentration in early morning is generally caused by increased output of pollutants into a relatively shallow heat island. This increased output is caused by increased burning of fuels for domestic purposes, starting up of non-continuous industries, and the morning traffic rush. The concentration in the air decreases later on in the day since more air is available for the pollutants to mix in as the heat island volume increases.

The morning peak concentration is not present in Edmonton. The reason for this seems to be that the increase in domestic burning in the morning does not result in a greater smoke output since the city uses natural gas for domestic purposes, which does not give off any particulate matter when burning. The afternoon peak is probably caused by greater vehicle activity and increased commercial burning of waste on one hand and decreased ventilation (mixing height - see page 49) on the other, during the afternoon period.

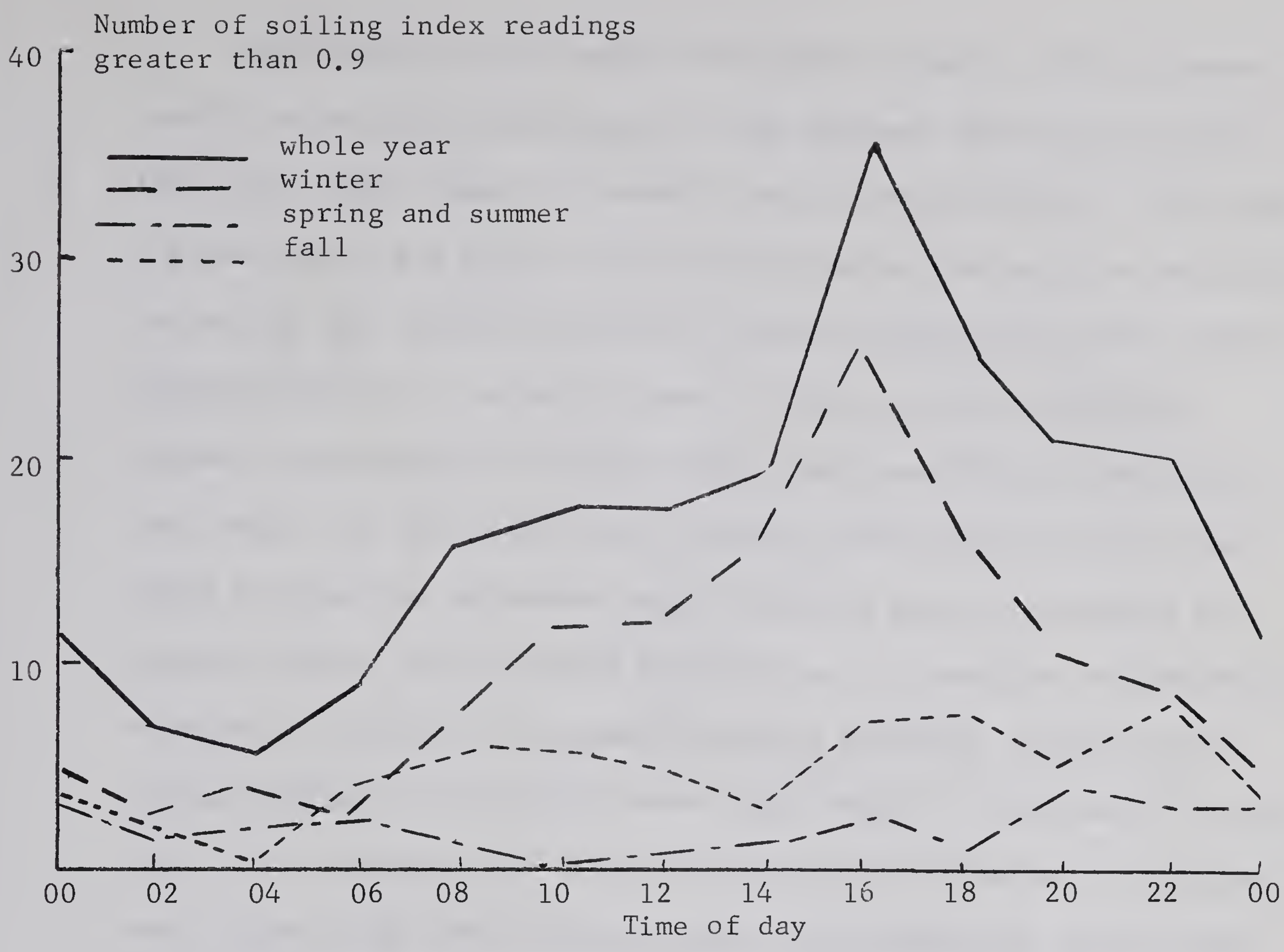

Fig. 26. Number of readings with soiling index larger than 0.9 at City Hall, Edmonton, by the hour, for 1963.
Source: D.T. Keenan, Air Pollution in Edmonton 1963, unpublished report to Government of Alberta, Dept. of Public Health, 1964.

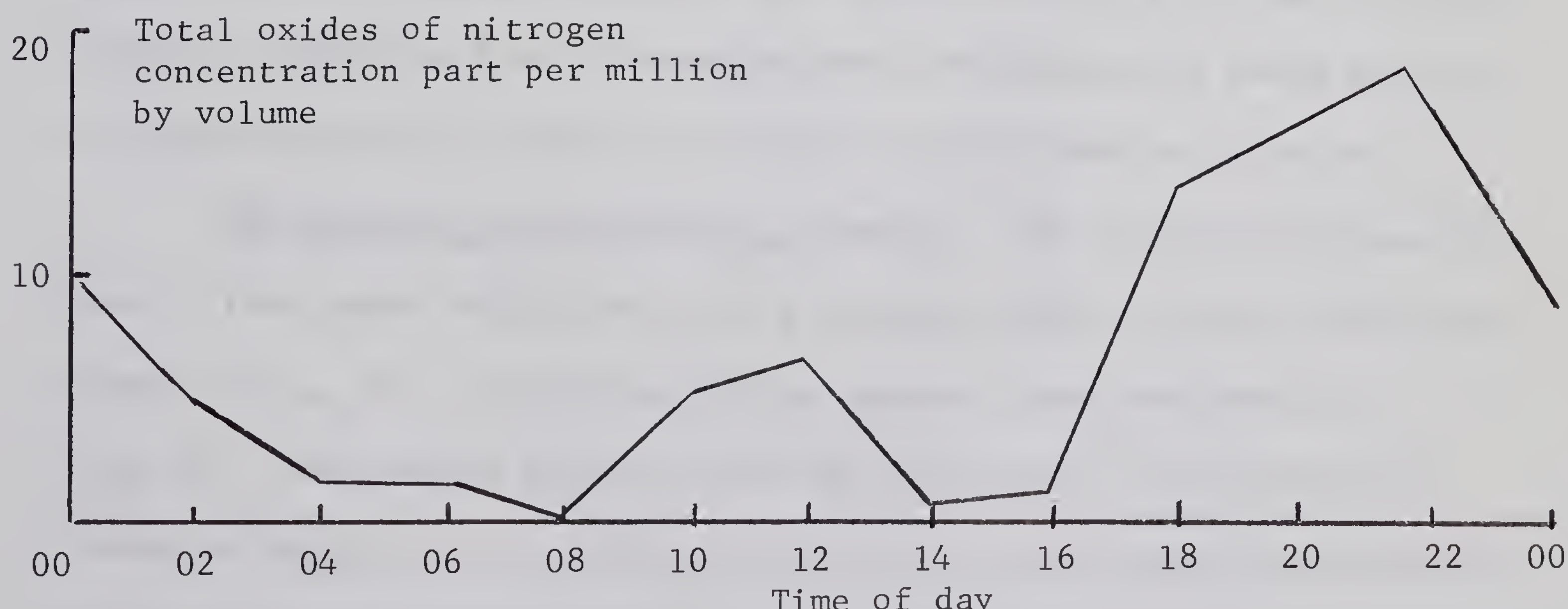

Fig. 27. The variation of total oxides of nitrogen concentration at Administration Building, Edmonton, by time of day, for 1963.
Source: D.T. Keenan, Air Pollution in Edmonton 1963, unpublished report to Government of Alberta, Dept. of Public Health, 1964.

The effects of decreased ventilation together with increased traffic activity is illustrated in the nitrogen oxide cycle as well (Fig. 27), where there is a marked peak in late afternoon. The reason for the lag of the peak is partly explained by the delay in replacing the air in the "traffic polluted" streets, especially in the central business district. As can be seen in Table 13, the emission of oxides of nitrogen is to almost 90 per cent incurred by traffic and fuel usage. As the latter does not have enough daily emission variation to cause the afternoon peak, this peak must be caused by increased traffic and decreased ventilation. The sampler for oxides of nitrogen is located in the Administration Building, roughly seven blocks northwest of the City Power Plant (Fig. 1). A total of 81 per cent of all readings with higher concentration of oxides of nitrogen than 1 ppm during 1963 were associated with winds from south, southeast and east. It is therefore obvious that the emission of oxides of nitrogen from the City Power Plant strongly affects the concentration level of these oxides at the Administration Building. The daily emission variation from this source also influences the daily cycle of the concentration of oxides of nitrogen at the sampling station.

<u>The Seasonal Concentration of Smoke</u>. The monthly averages for the soiling index during the period December 1959 to January 1963 are shown in Fig. 29. The corresponding seasonal ones are shown in Fig. 28. The average seasonal soiling indexes for this period are shown in Table 15. A comparison with other cities shows that seasonal variation in the soiling index is less for Edmonton than for other cities. The reason for this is probably that natural gas, emitting no particulate matter when burning, is used for heating purposes in

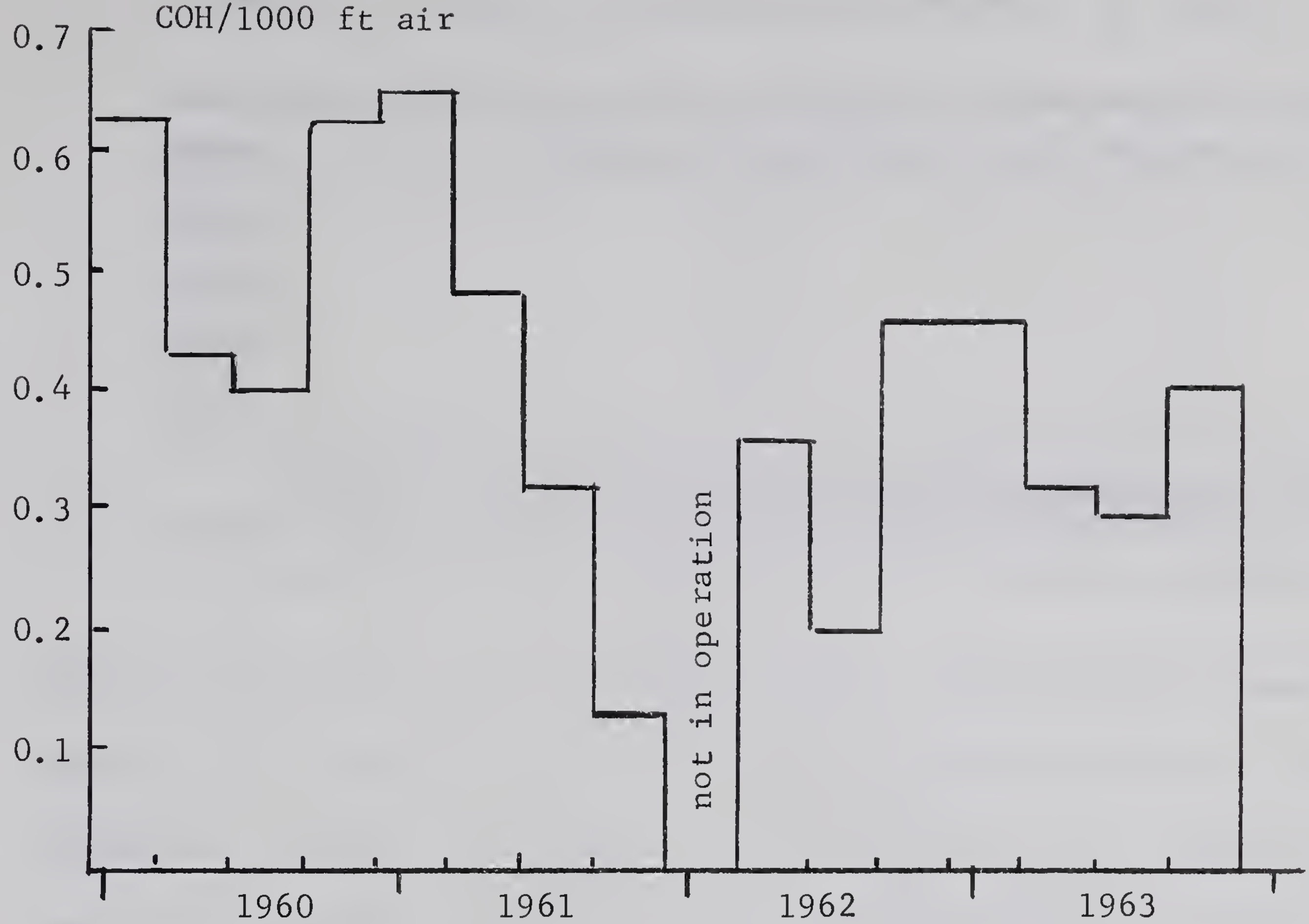

Fig. 28. The variation of smoke concentration by seasons, at City Hall, Edmonton
Source: D.T. Keenan, <u>Air Pollution in Edmonton 1963</u>, unpublished report to Govt. of Alberta, Dept. of Public Health, 1964.

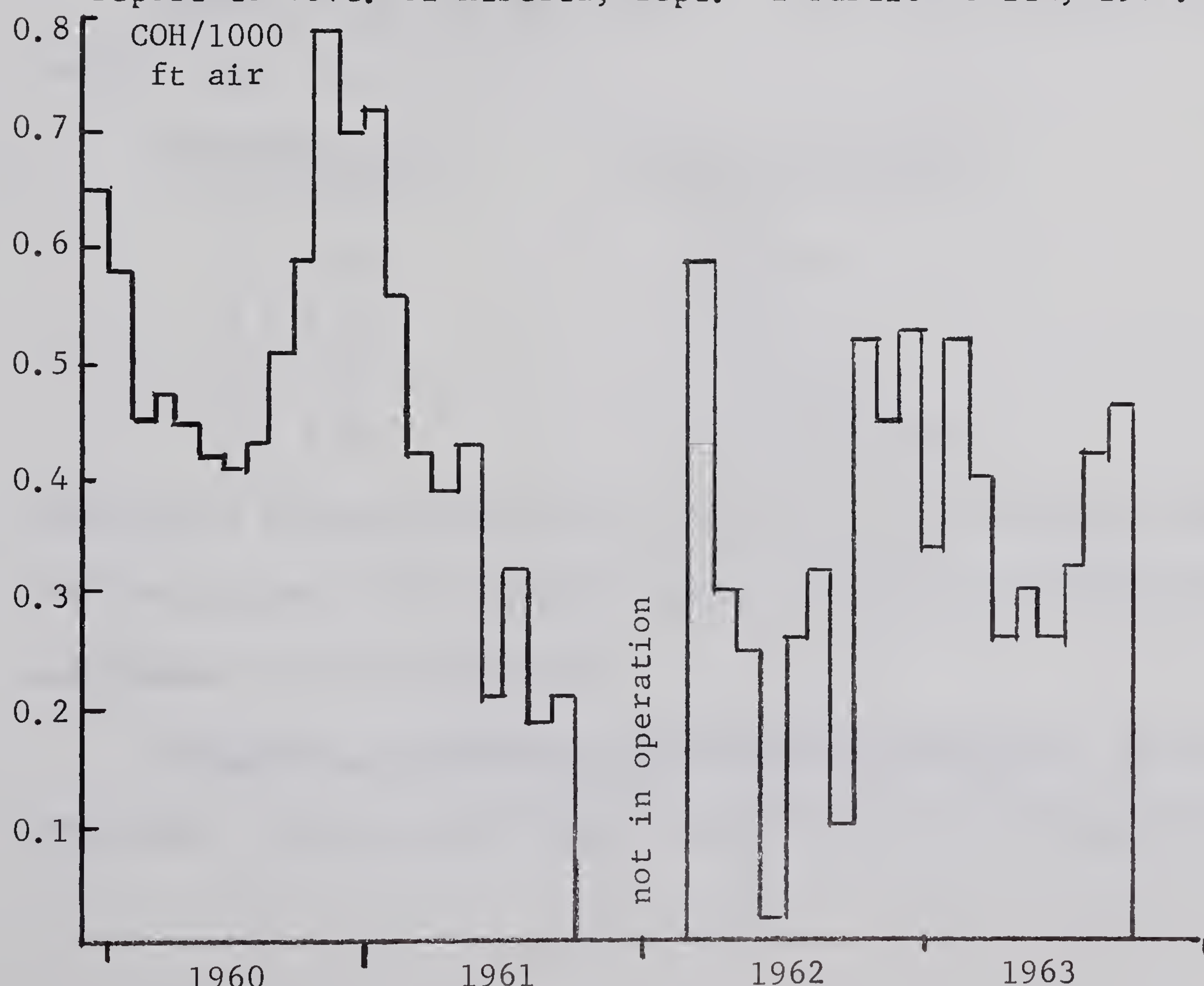

Fig. 29. The variation of smoke concentration by the month, at City Hall, Edmonton
Source: D.T. Keenan, <u>Air Pollution in Edmonton 1963</u>, unpublished report to Govt. of Alberta, Dept. of Public Health, 1964.

TABLE 15 - MEAN SOILING INDEX FOR EDMONTON, BY SEASON

Season	Mean soiling index	No. of Seasons Used
Winter	0.60	3
Spring	0.40	4
Summer	0.31	3
Fall	0.41	4

Source: D.T. Keenan, Air Pollution in Edmonton, unpublished report to Govt. of Alberta, Dept. of Public Health, 1964.

the city, thus there is no influence on the concentration of particulate matter by the heating cycle. As the other emitting sources in the city, industries, traffic and garbage burning probably have no seasonal cycle, the seasonal variations of the soiling index are probably caused by meteorological conditions (see page 115).

Rating of the soiling index. A generally accepted scale of the soiling index is as follows:

COH/1000 ft air	Degree of pollution
0 - 0.9	light
1 - 1.9	moderate
2 - 2.9	heavy
3. - 3.9	very heavy
4 - 4.9	extremely heavy

The highest observed figure for Edmonton is 4.0 (25/9/64), which is very low compared with the maxima for other cities such as Montreal's 12.8 and Sydney's 23.0 in Australia.

Variation of soiling index with wind direction. The hours during 1963 with a soiling index higher than 0.9 have been divided into classes

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according to the actual wind speed and direction. The result of this investigation is shown in Table 16, where the number of two-hour periods with higher soiling index than 0.9 are given as well as the ratio of the "polluted" hours to the total number of hours of wind in each class. The percentages are shown in Fig. 30 as well.

As can be seen, the percentage of "polluted" periods decreases rapidly when the wind speed increases. In Fig. 30 there are two directions for which the curves are different from the others, south and southwest. This suggests that the main source of pollution in these two directions is similar but of a different kind from the other directions. These sources, most probably the traffic, and, less important, the burning of commercial waste are concentrated south and southwest of City Hall. A third direction where these kinds of sources are important is west, but as the source survey for the city showed, the emission from traffic and commercial waste is perhaps not so predominant there as it is for the south and southwest. There are several large industries in the western section of the city.

The hours with a soiling index larger than 0.9 were also calculated as per cent of total number of hours by wind direction and the time of day. The result of this investigation is shown in Table 17. As can be seen in this table, the occurrence of high concentration with winds from the south and southwest is approximately three times greater in the afternoon than in early morning. This fact will be used in Chapter XIII to estimate the emission of pollutants in these two sectors of the city. Because of the limited number of observations an elaborate analysis of the variations with time and wind direction would yield uncertain results.

TABLE 16 - THE NUMBER OF HOURLY WIND OBSERVATIONS BY SPEED AND DIRECTION (w), THE NUMBER OF TWO-HOUR PERIODS WITH A SOILING INDEX LARGER THAN 0.9, EXPRESSED IN ABSOLUTE FIGURES (p) AND AS A PERCENTAGE OF THE TOTAL NUMBER OF WIND OBSERVATIONS FOR EACH CLASS (%) DURING 1963

Wind speed		N			NE			E			SE			S	
(mi/h)	p	w	%	p	w	%	p	w	%	p	w	%	p	w	%
1-2	3	57	10.5	2	36	11.1	4	56	14.3	2	49	8.2	8	84	19.0
1-4	6	168	7.1	7	119	11.8	11	209	10.5	7	194	7.2	27	440	12.3
1-6	9	300	6.0	9	220	8.2	19	387	9.8	10	337	5.9	48	948	10.1
1-8	10	440	4.5	11	310	7.1	19	539	7.1	12	595	4.0	67	1275	10.5
1-10	11	603	3.6	14	420	6.7	19	659	5.8	13	823	3.2	69	1432	9.6
1-30	11	1250	1.8	14	592	4.7	21	868	4.8	13	1455	1.8	70	1596	8.8

Wind speed		SW			W			NW			All directions	
(mi/h)	p	w	%	p	w	%	p	w	%	p	w	%
1-2	3	61	9.8	4	48	16.7	1	20	10.0	27	428	12.6
1-4	10	235	8.5	13	177	14.7	3	87	6.9	84	1653	10.2
1-6	15	525	5.7	17	358	9.5	4	184	4.3	131	3323	7.9
1-8	21	766	5.5	20	527	7.6	5	298	3.4	166	4784	6.9
1-10	22	910	4.8	21	711	5.9	6	409	2.9	175	5991	5.8
1-30	24	1020	4.7	25	1126	4.4	9	829	2.2	187	8736*	4.3

* 24 hours with no wind, of which two hours had a larger soiling index than 0.9

For example: Of all the hours with northern winds during 1963 (1250 hrs), 440 had a wind speed of 1-8 mph. Of all two-hour periods with soiling index larger than 0.9 during 1963 (187 periods), 11 occurred with northern winds (if the wind changed during the two-hour period, the first hour direction and the mean speed were used; however this occurred seldom). Of the 11 occasions with northern winds, 10 occurred with wind speeds of 1-8 mph. Thus 20 hours (10 two-hour periods) were "polluted" which makes 4.5 per cent of the total number of hours with northern winds at 1-8 mph (440 hours).

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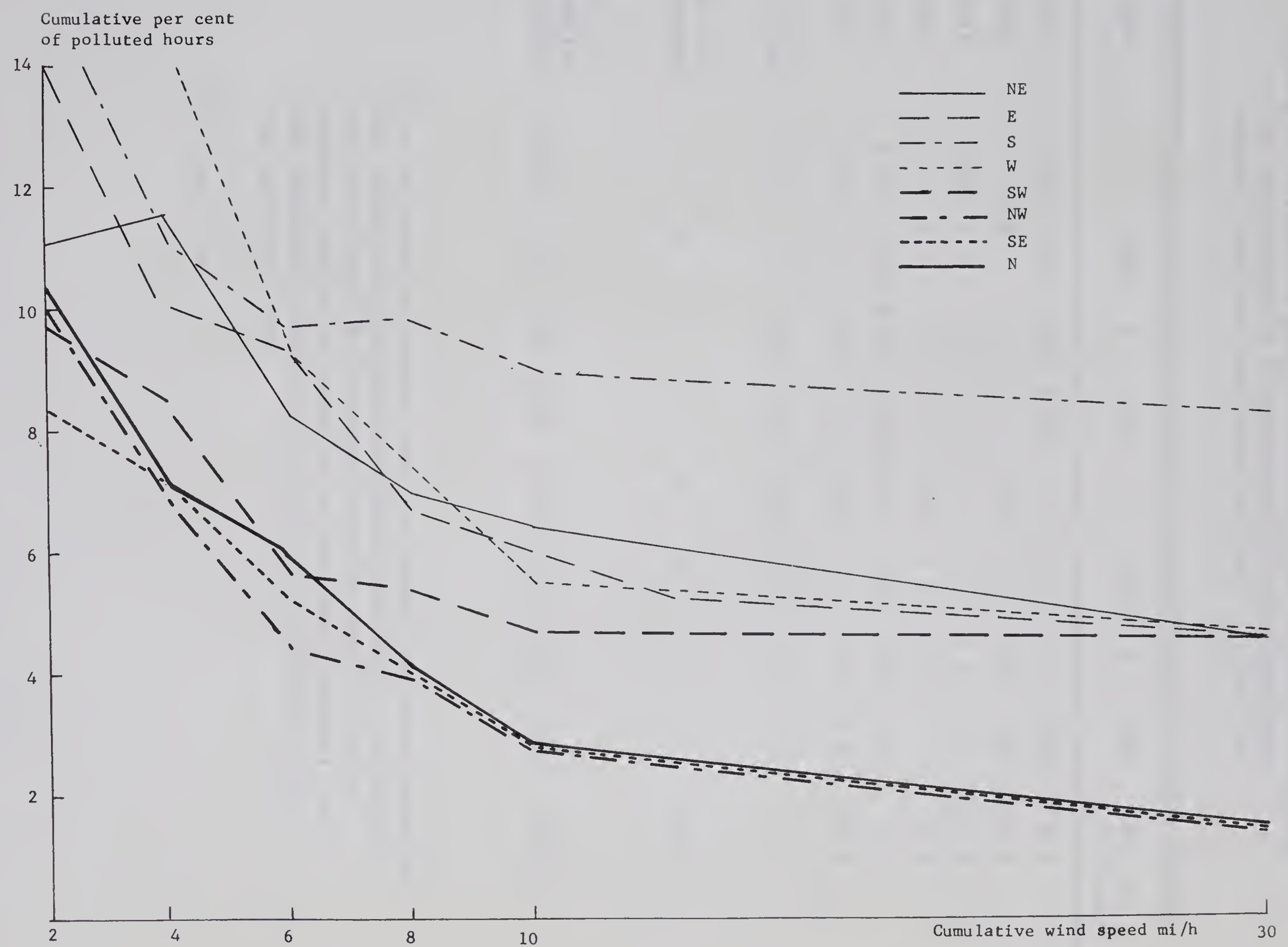

Fig. 30. The cumulative number of polluted hours as a per cent of cumulative wind speed, by wind directions during 1963.

TABLE 17 - TWO-HOUR PERIODS WITH SOILING INDICES LARGER THAN 0.9, CALCULATED AS A PERCENTAGE OF WIND DIRECTION OBSERVATIONS FOR FOUR-HOUR PERIODS,[1] DURING 1963

Time	N	NE	E	SE	S	SW	W	NW	All directions
22-02	1.0	8.1	2.8	0.8	3.0	3.5	2.1	1.5	2.6
02-06	0	0	4.2	0	5.3	1.2	5.3	1.5	2.5
06-10	1.0	6.1	1.4	0	10.5	4.7	3.2	1.5	3.9
10-14	1.0	4.1	4.2	3.3	8.3	8.2	4.3	0	4.1
14-18	2.9	2.0	8.3	3.3	14.3	5.9	7.5	4.3	7.0
18-22	4.8	8.1	8.3	3.3	11.3	4.7	4.3	4.3	6.6
All day	1.7	4.7	4.8	1.8	8.8	4.7	4.4	2.1	4.3
No. of readings	11	14	21	13	70	24	25	9	187
No. of hourly wind obs.	1250	592	868	1455	1596	1020	1126	829	8736[2]

[1]This calculation assumes that the winds from each direction were evenly distributed throughout the day. The winds from the north, for example, were not assumed to be dominant during any particular four-hour interval, but were assumed to be evenly distributed throughout the six intervals used.

[2]24 hours calm

Weather situations giving high concentration of pollutants. The weather situations during 1963 at which a soiling index higher than 0.9 occurred were investigated with the aid of the daily weather maps. There were mainly two kinds of situations resulting in high concentrations:

(a) Quasistationary high pressure systems centered close to Edmonton, associated with low winds and downwards air movements

(b) Trapping of air under a quasistationary front with warm air aloft preventing vertical air movements

The situations were evenly distributed between the two types. These findings are in accord with several other studies.[15]

[15]For instance: F.K. Davis Jr., "The Air Over Philadelphia," Symposium Air Over Cities, SEC Technical Report A62-5, p. 119; G. Pézley, "Die Luftverureinungen in Budapest bei verschiedene Macrosynoptische Lagen," Zeits. f. Met., Band 13, Heft 1-6, 1959; P.W. Summers, "Smoke Concentrations in Montreal," Symposium Air Over Cities, SEC Technical Report A62-5, p. 95.

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CHAPTER XII

THE URBAN HEAT ISLAND MODEL AND THE DISPERSION OF POLLUTANTS

A. Literature on the Vertical Distribution of Pollutants

As pointed out earlier, the heat from the city creates a pillow of warm air over the city (the heat island). Artificial heat and heat absorbed by concrete and asphalt in the city warm the surface air, thereby causing it to rise in convective eddies. The substantially increased mechanical turbulence also causes vigorous vertical air movements over the city. It can therefore be assumed that the air over the city is vertically almost completely mixed to the top of the heat island (the mixing height). As the weight of the pollutants (gaseous and solids) is negligible it can be assumed that they follow the air movements, and thus are rapidly mixed vertically throughout the heat island.

This mixing of pollutants over the city is confirmed by the relatively few actual measurements on the vertical distribution of particulate matter that have been undertaken. The most important of these studies are mentioned below.

Löbner[1] found three maxima of pollution concentration (street level, roof level and industrial stack level) in Leipzig, but the average increase of pollutants with height up to 70 m was nil.[2]

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[1] A. Löbner, "Horizontale und vertikale Staubverteilung in einer Gross-stadt," Veröffentlichungen des geophysikalichen Instituts der Universität Leipzig, 2 Serie, Band 7, Heft 2, 1935, pp. 53-99.

[2] P.A. Kratzer, Das Stadtklima, Braunschweig, 1956, p. 30.

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Davidson[3] found in analyzing readings from seven smoke samplers in New York that there was no systematic change in the concentration of pollutants up to 300 ft.

Summers[4] got the same result from observations made in Montreal with a portable smoke sampler along the route from the downtown area to 500 ft up the slopes of Mount Royal within the city.

The International Joint Commission studying air pollution in the Detroit River area found:[5]

> The results indicate that the differences in rate of pollution emission at the two levels (2 and 125 ft), vertical mixing rates, wind direction and rate of particle fall act jointly in such a manner that particulate pollution levels in the lowest 125 ft above ground are essentially uniform at this location (the Majestic Building, Detroit) on an average basis.

Although Grisollet and Pelletier[6] found differences in the amount of pollutants at the 12 and 53 meter levels in Paris, they were only of the order of 6 per cent to 9 per cent.

In the most extensive study, McCormick and Baulch[7] investigated the air over Cincinnati, Ohio, using a helicopter. They found the pollution stratified but the whole bulk of pollution was under the inversion layer (i.e. up to the mixing height).

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[3] W.F.Davidson, "A Study of Atmospheric Pollution," Monthly Weather Review, 70, 1942, p. 225.

[4] P.W. Summers, "An Urban Heat Island Model, its Role in Air Pollution Problems, with Applications to Montreal," A paper presented at the First Canadian Conference on Micrometeorology, Toronto, 1965, p. 3.

[5] International Joint Commission, Pollution of the Atmosphere in the Detroit River Area, Ottawa, 1960, p. 184.

[6] H. Grisollet and J. Pelletier, "La pollution atmosphérique au centre de Paris et ses relations avec quelques facteurs climatologiques," La météorologie, juillet-septembre, 1957, p. 412.

[7] R.A. McCormick and D.M. Baulch, "The Variation with Height of the Dust Loading over a City as Determined from the Atmospheric Turbidity," J. Air Poll. Control Assoc., 12, 1962, p. 492.

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The conclusions reached from the relatively few investigations of the vertical distribution of pollutants support the hypothesis that throughout the heat island the pollutants from a specific source quickly disperse uniformly vertically.

B. Theoretical Basis for Calculation of the Concentration

The problem to be considered is as follows: given a continuous emission of rate E from a source, what will the concentration be at a point downwind from the source, assuming a constant wind speed u.

To solve this problem one generally employs the Cartesian coordinate system with the point of origin at the source and with the x-direction as the mean wind direction, y-direction crosswind and the z-direction vertically. The problem is, then, generally approached from a statistical point of view, where certain probability density functions at the diffusion of pollutants are assumed.[8] This statistical approach will be used below.

The total amount of pollutants per time unit passing through any cross-section of infinite height and length downwind from the source is constant, since we are dealing with a continuous source and the wind speed is assumed constant. This means that the diffusion in x-direction, disregarding the diffusion of pollutants in any other direction, is nil which implies that the probability density function in x-direction, $d(x)$ is $d(x) = 1$.

The distribution of pollutants in y-direction is assumed to be that of the normal curve[9] with a standard deviation of σ_y. The pro-

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[8]If a variable, x, varies continuously over some interval and there is a probability, $f(x)$, that the variable takes a value between x and $x + dx$, $f(x)$ is the probability density function.

[9]M.R. Spiegel, Statistics, New York, 1961.

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bability density for the concentration in y-direction, f(y), is thus:

$$f(y) = \exp(-y^2/2\sigma_y^2) \;/\; (2\pi)^{1/2}\sigma_y \qquad \text{(XII.1)}$$

The distribution of pollutants in z-direction is assumed to be uniform with height up to the top of the heat island, h. The probability density g(z) is thus:

$$g(z) = 1/h \qquad \text{(XII.2)}$$

The joint probability density for the concentration distribution (x,y,z) is:

$$\chi(x,y,z) = d(x)\ f(y)\ g(z) = \exp(-y^2/2\sigma_y^2)/(2\pi)^{1/2}\sigma_y h \qquad \text{(XII.3)}$$

as the three linear variables are independent.

The concentration is directly proportional to the emission rate, E, and indirectly proportional to the wind speed, u. The complete expression for the concentration is thus given by:

$$\chi(x,y,z) = d(x)\ f(y)\ g(z)\ E/u = E \exp(-y^2/2\sigma_y^2)/\ (2\pi)^{1/2}\sigma_y h\ u \qquad \text{(XII.4)}$$

This expression developed by the author is simpler than the one usually used,[10] where the density in z-direction also is assumed to be that of the normal curve. This expression is as follows:

$$\chi(x,y,z) = E \exp(-y^2/2\sigma_y^2) \left[\exp\left(\frac{-z-H^2}{2\sigma_z}\right) + \exp\left(\frac{-z+H^2}{2\sigma_z}\right)\right] \Big/ \pi\sigma_y\sigma_z\ u \qquad \text{(XII.5)}$$

where:

H = the effective stack height i.e. the sum of the actual height of the stack, the height of the rise of the smoke caused by the smoke exit velocity, and the height of the smoke rise caused by the excess in temperature of the smoke compared with the air.[11]

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[10] For instance: D.B. Turner, "A Diffusion Model for an Urban Area," J. Appl. Met., Vol. 3, No. 1, 1964, pp. 83-91.

[11] H. Moses and G.H. Strom, "A Comparison of Observed Plume Rise with Values Obtained from Well-known Formulas," J. Air Poll. Control Assoc., Vol. 11, No. 10, 1961, pp. 455-466.

σ_z = the standard deviation in z-direction.

This formula (XII.5) was first arrived at by Sutton[12] and later simplified by Cramer[13] and Gifford.[14,15]

The standard deviations σ_y and σ_z. These quantities depend on the roughness of the surface and the stability of the air. Theoretical studies[16] indicate that the plume starts out in the vicinity of the source as a cone, later on to become a paraboloid. This is in agreement with actual observations. Actual measurements of the coefficients were made at Project Prairie Grass. Graphs for different vertical stability classes were constructed by Cramer[17] and Gifford[18] employing these data (Fig. 31). The height of the plume, H, was defined as the height at which the concentration is 10 per cent of the concentration at the axis. This appears[19] to approximate the visible edge of the plume. The quantities σ_z and H are related as: $H = 2.15\,\sigma_z$.

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[12] O.G. Sutton, "The Problem of Diffusion in the Lower Atmosphere," Quart. Journ. R. Met. Soc., Vol. 73, 1947, p. 273.

[13] N.E. Cramer, "A Brief Survey of the Meteorological Aspects of Atmospheric Pollution," Bull. Amer. Met. Soc., Vol. 40, No. 4, 1959, pp. 165-171.

[14] F.A. Gifford, "Atmospheric Dispersion," Nuclear Safety, Vol. 1, No. 3, 1960.

[15] Idem., "Atmospheric Dispersion Calculations Using the Generalized Gaussian Plume Model," Nuclear Safety, Vol. 2, No. 4, 1961.

[16] G.I. Taylor, "Turbulence," Quart. Journ. R. Met. Soc., Vol. 53, 1927, p. 201.

[17] Cramer, op.cit.

[18] F.A. Gifford, "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," Nuclear Safety, Vol. 2, No. 2, 1960.

[19] Ibid.

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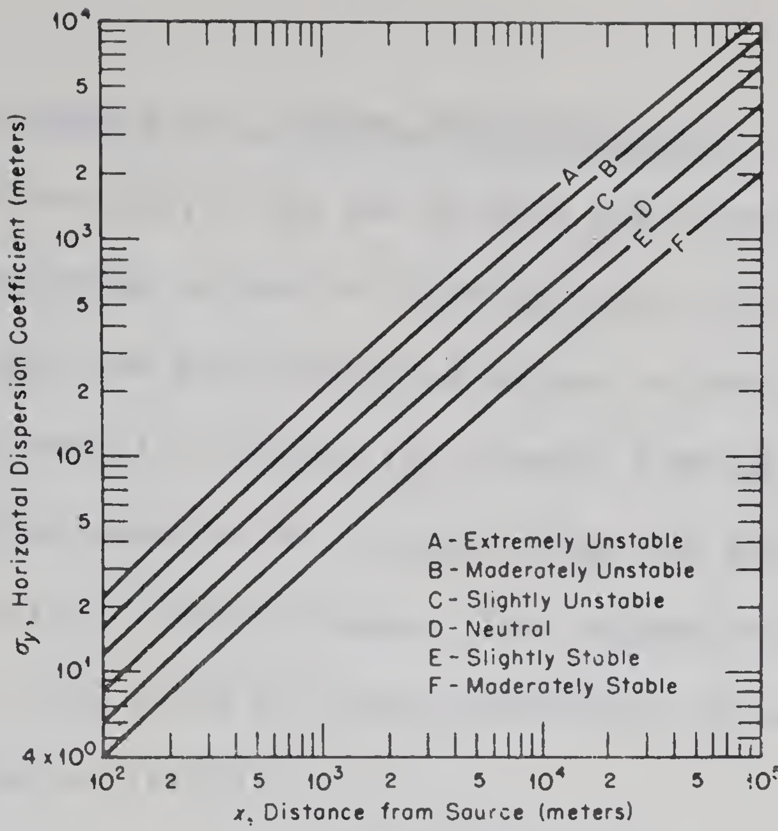

Fig. 31A. Horizontal dispersion coefficient as a function of distance from source.

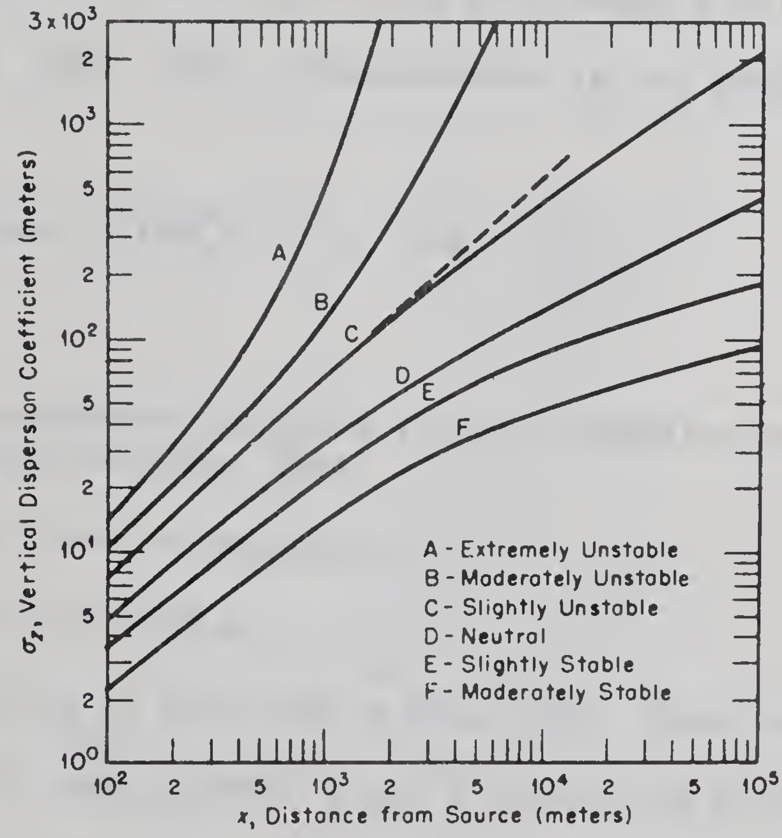

Fig. 31B. Vertical dispersion coefficient as a function of distance from source.

Source: F.A. Gifford, "Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion," Nuclear Safety, Vol. 2, No. 4, 1961.

C. The Dispersion Formula for Varying Wind Directions

To use equation (XII.4) one has to know the exact wind direction. It is therefore impossible to use the wind reported only by the eight cardinal points. This can be illustrated by the following example:

Assume that there is a source (S) located 2 km in the bearing 112° from the sampling station (A). Suppose that the wind is blowing from the same direction, listed as east. This situation is shown in Fig. 32. Since y = 0 at point (A) the concentration at the sampling spot (A) is according to (XII.4):

$$C = E / h\ u\ (2\pi)^{1/2} \sigma_y \qquad \text{(XII.6)}$$

Now suppose that the wind changed over to 68°, which still would be listed as east (Fig. 32b). The concentration at the sampling spot (A) would now be:

$$C = E \exp(-y_1^2/2\sigma_y^2) / h\ u\ (2\pi)^{1/2} \sigma_y \qquad \text{(XII.7)}$$

where:

y_1 = the perpendicular distance from the sampling spot (A), to the x-axis (see Fig. 32b)

y_1 can be calculated from the relation:

y_1 = 2000 sin 44 = 1390 m.

σ_y for neutral stability is about 100 m (Fig. 31). Thus the exponential expression in (XII.7): exp $(-1390^2/ 2\ 100^2)$ = exp (-96.7) which is approximately 0. The concentration with wind from this direction thus does not correspond very well with that of wind from 77°, although both directions are listed as east. It is necessary to modify equation (XII.4) so that it will account for the variation of the wind within one of the main octants. To arrive at this modified expression for the concentration, assume the situation as shown in Fig. 33.

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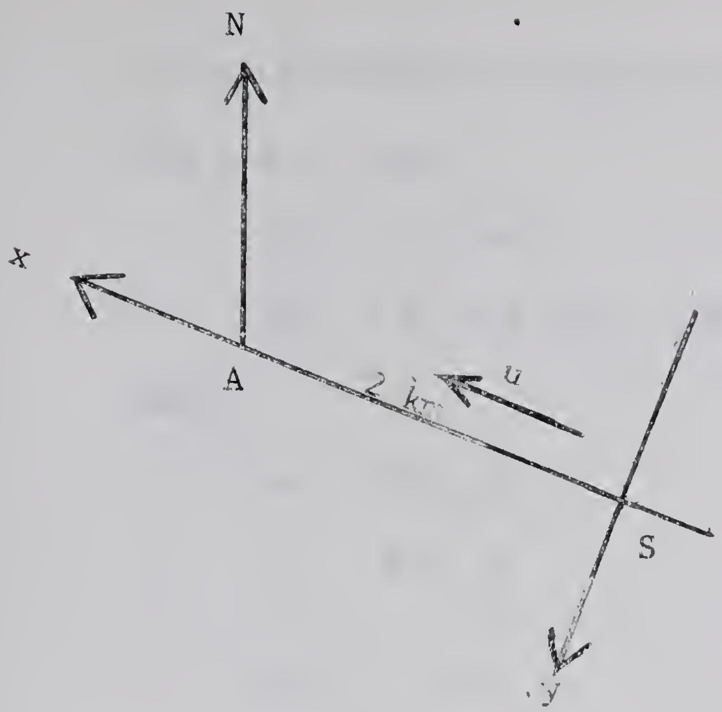

Fig. 32a. The situation with the wind blowing from [illegible]°.

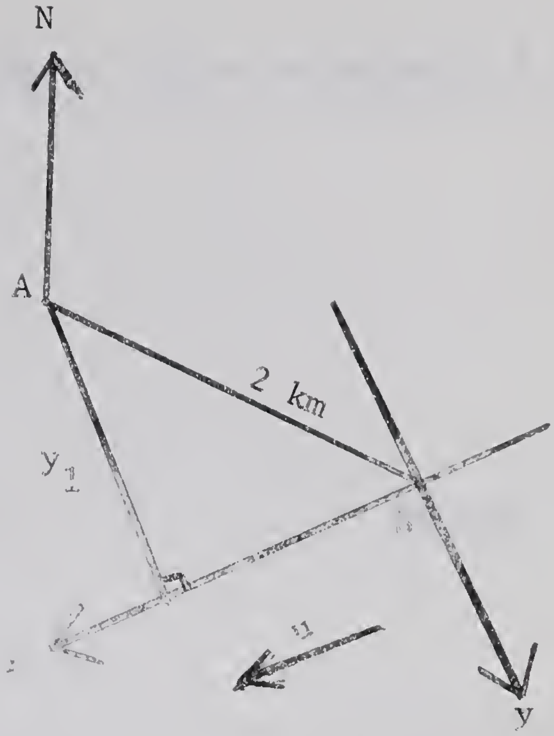

Fig. 32b. The situation with the wind blowing from 68°.

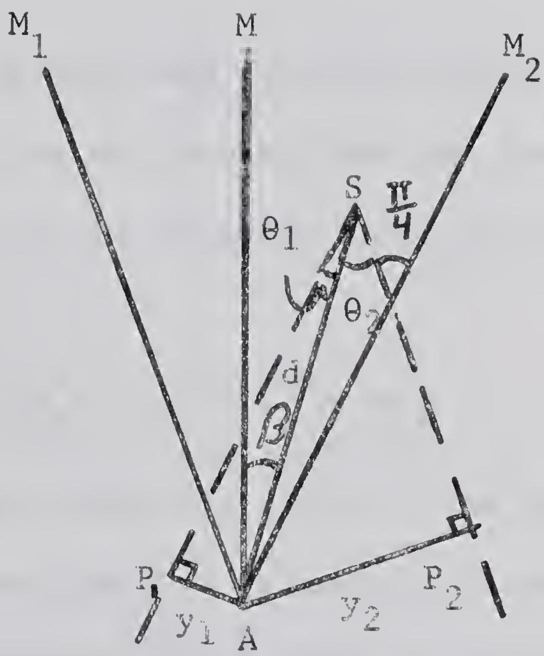

Fig. 33. Calculation of concentration for varying wind directions (see text).

<u>Legend</u>:

A - the sampling spot
S - the source emitting at a rate of E
d - the distance between the source and the sampling spot
MA - one of the eight main directions.
$M_1AM = M_2AM = \pi/8$
β = the angle between the direction from the source to the sampling spot and the main direction
SP_1 - parallel with M_2A
SP_2 - parallel with M_1A
y_1 - the perpendicular distance from the sampling spot to line SP_1
y_2 - the perpendicular distance from the sampling spot to line SP_2
θ_1 - the angle between AS and SP_1
θ_2 - the angle between AS and SP_2

It can be shown by considering exterior angles of the triangles S A P_1 and S A P_2 that:

$$\theta_1 + \theta_2 = \pi/4$$

$$\pi/2 - \theta_1 + \beta + \pi/8 = \pi/2$$

Thus:

$$\theta_1 = \pi/8 - \beta \qquad \theta_2 = \pi/8 + \beta \tag{XII.8}$$

$$\sin \theta_1 = y_1 / d$$

$$\sin \theta_2 = y_2 / d$$

$$y_1 = d \sin(\pi/8 - \beta) \qquad y_2 = d \sin(\pi/8 + \beta) \tag{XII.9}$$

To use this equation it is not necessary that the source be within the angle $M_1 A M_2$. Let the wind first be blowing from the direction $M_1 A$ with a speed u. The concentration at the sampling spot, C_1^1, is according to (XII.4):

$$C_1^1 = E \exp(-y_1^2 / 2\sigma_y^2) / (2\pi)^{1/2} h u \sigma_y \tag{XII.10}$$

Now let the wind shift to a new direction close to the earlier one and within the angle $M_1 A M_2$, so that the new value on y is one length unit less, $(y_1 - 1)$. The concentration at the sampling spot in this situation, C_2^1, is:

$$C_2^1 = E \exp(-(y_1 - 1)^2 / 2\sigma_y^2) / (2\pi)^{1/2} h u \sigma_y \tag{XII.11}$$

Let the wind continue to shift in the same manner, each time giving a new value of y, which is one unit less than the previous one. Every direction so chosen will give an expression for the concentration similar to (XII.11).

The average concentration for these wind directions, C^1, is:

$$C^1 = \left[C_1^1 + C_2^1 + \ldots . C_{y_1} \right] / \; y_1 = \frac{E}{h\; u\; (2\pi)^{1/2} \sigma_y} \sum_{i=0}^{y_1} \exp(-i^2/2\sigma_y^2) \qquad \text{(XII.12)}$$

as there have been y_1 different wind situations.

Let the wind shift in the same manner in the other section M A M_2.

For this side the average concentration, C^2, is:

$$C^2 = \left[C_1^2 + C_2^2 + \ldots . C_{y_2} \right] / \; y_2 = \frac{E}{h\; u (2\pi)^{1/2} \sigma_y} \sum_{i=0}^{y_2} \exp(-i^2/2\sigma_y^2) \qquad \text{(XII.13)}$$

The total average concentration, C_{av}, is thus:

$$C_{av} = \left[\sum_{i=0}^{y_1} \exp(-i^2/2\sigma_y^2) + \sum_{i=0}^{y_2} \exp(-i^2/2\sigma_y^2) \right] E \; / \; h\; u\; (2\pi)^{1/2} \sigma_y (y_1 + y_2) \qquad \text{(XII.14)}$$

The sums in the above expression can be written as integrals. Thus:

$$C_{av} = \left[\int_0^{y_1} \frac{\exp(-v^2 \; / \; 2\sigma_y^2)}{(2\pi)^{1/2} \sigma_y} dv + \int_0^{y_2} \frac{\exp(-v^2 / \; 2\sigma_y^2) \; dv}{(2\pi)^{1/2} \sigma_y} \right] E / _{(y_1 + y_2)} h\; u \qquad \text{(XII.15)}$$

The integral expressions are of "error-function" type, defined as:

$$\Phi \; (x) = \int_{-\infty}^{x} \frac{\exp(-v^2/2\sigma_y^2)}{(2\pi)^{1/2} \sigma_y} dv$$

It is impossible to solve this integral, but there are tables worked out for the integral.[20]

With the error-function symbol (XII.15) can be written:

$$C_{av} = \frac{E \left[\Phi (y_1/\sigma_y) + \Phi (y_2/\sigma_y) - 1 \right]}{h\; u\; (y_1 + y_2)} \qquad \text{(XII.16)}$$

With y_1 and y_2 replaced with the expressions in (XII.9) the equation becomes:

$$C_{av} = \frac{E \left[\Phi \; (d \sin(\pi/8 - \beta)/\sigma_y) + \Phi \; (d \sin(\pi/8 + \beta) / \sigma_y) - 1 \right]}{h\; u\; d \left[\sin \; (\pi/8 - \beta) + \sin \; (\pi/8 + \beta) \right]} \qquad \text{(XII.17)}$$

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[20] For instance: M.R. Spiegel, Statistics, New York, 1961, p. 343.

The trigonometric expression in the denominator can be written:

$$\sin(\pi/8+\beta) + \sin(\pi/8-\beta) = 2\sin(\pi/8)\cos\beta = 0.765\cos\beta \qquad \text{(XII.18)}$$

The actual angle of the main direction, α, can be introduced in equation (XII.17) by replacing β with $|\alpha - \beta'|$. β' now being the angle between the line from the sampling spot to the source and the north direction line through the sampling spot (Fig. 34). However $|\alpha-\beta'|$ must be less than $\pi/4$, if the source shall give any contribution to the concentration at the sampling spot.

With this change (XII.17) can be written with (XII.18):

$$C_{av} = \frac{E\left[\Phi(d\sin(\pi/8 - |\alpha-\beta'|)/\sigma_y) + \Phi(d\sin(\pi/8 + |\alpha-\beta'|)/\sigma_y) - 1\right]}{h\,u\,d\,0.765\cos(|\alpha-\beta'|)} \qquad \text{(XII.19)}$$

The total concentration, C, from all sources in the area surrounding the sampling spot can be calculated by summing (XII.19) for all sources upwind N:

$$C = \frac{1}{u\,0.765\,h}\sum_{i=1}^{N} E_i \frac{\left[\Phi(d_i\sin(\pi/8 - |\alpha-\beta_i'|)/\sigma_{yi}) + \Phi(d_i\sin(\pi/8 + |\alpha-\beta_i'|)/\sigma_{yi}) - 1\right]}{d_i\cos(|\alpha-\beta_i'|)} \qquad \text{(XII.20)}$$

where the wind is blowing from one of the eight main directions, α, at a speed of u, and the mixing height is h. The sources used have to fulfill the requirement that $|\alpha-\beta'| < \frac{\pi}{4}$

For sources not too close to the sampler within a 30° sector around the main direction, α, i.e. $|\alpha-\beta|<15°$ the error functions in the expressions above are approximately 1 as $\left[\frac{d}{\sigma_y}\sin\left(\frac{\pi}{8} - |\alpha-\beta'|\right)\right] \geq \left[\frac{d}{\sigma_y}\sin(7.5)\right] \gg 3$ as $d \gg \sigma_y$ (Fig. 31). Thus for these sources the following simplified expression holds:

$$C_{av} = E / h\,u\,d\,0.765\cos(|\alpha-\beta'|) \qquad \text{(XII.21)}$$

For sources with a larger angle of deviation than 30° from the main direction, α, i.e. $|\alpha-\beta'| > 30°$ the contribution at the sampling spot is

generally 0. The expression (XII.19) has some advantages compared with Sutton's equation (XII.5):

1. The vertical diffusion coefficient, σ_z, does not need to be known. This is an important advantage since pollution calculations generally are carried out for urban areas where there is a definite change of σ_z at the top of the heat island, and thus to get an exact calculation one must use two distinct values for σ_z, one for the occasion when the pollutants are below the heat island, and another when they are above it.

2. The assumption that the ground acts as a perfect reflector for the pollutants does not have to be made.

3. For sources within 15° from the wind direction, the horizontal dispersion coefficient, σ_y, does not have to be known in general, since the error functions can be assumed to be 1 here.

4. The result is independent of the height at which the pollutants are measured.

5. The effective stack height does not have to be known. This is of great advantage because the computing of the effective stack height is generally very complicated.

6. This expression is much simpler than Sutton's. Its greatest drawback is that so far too few actual measurements of the vertical pollution distribution have been made that confirm the assumed uniform concentration with height.

The equation (XII.16) is applied to Edmonton (Chapter XIII).

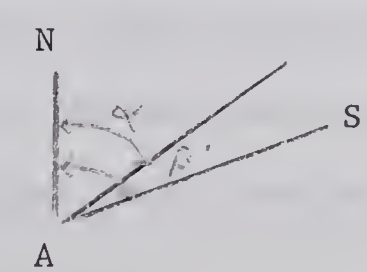

Fig. 34. Introduction of the main wind direction, α.

CHAPTER XIII

THE MODEL WITH UNIFORM VERTICAL MIXING OF POLLUTANTS WITHIN THE HEAT ISLAND APPLIED TO EDMONTON

By using equation (XII.19) it is possible to calculate the concentration of pollutants at a given location if the following parameters are known:

(a) the number of occurrences of wind from each of the eight main directions;

(b) the mean maximum difference in temperature between the city and the country for each main direction;

(c) the mean lapse rate over the country for each main direction;

(d) the mean wind speed for each main direction;

(e) the location and rate of emission of all sources affecting the concentration at the sampling spot.

This calculation of the concentration for each of the eight main directions was carried out for Edmonton for the daily periods 0400 to 0600 and 1400 to 1600 during the following eight winter months: Jan. 1961, Feb. 1961, Dec. 1962, Jan. 1963, Feb. 1963, Dec. 1963, Jan. 1964, and Feb. 1964. The reason for choosing these months was that concentration of pollutants in winter time is much greater (see page 109) and that only for the winter months mentioned above are there useful records of the concentration of particulate matter in Edmonton. The periods of the day were chosen to coincide with the times of ascent of the radiosonde balloon at Edmonton.

A. Meteorological Parameters

The meteorological parameters used in the calculations were as

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follows: The mean maximum difference in temperature between the city and the country was assumed to be 3°C for all directions both 0500 and 1700 hrs. The temperature traverses in winter showed a maximum city-country difference of 3.3°C in early morning and 2.7°C in late afternoon (see page 40). The average figure, 3°C, was chosen since the discrepancy between the early morning and the late afternoon value was not assumed to be so large that it was worth accounting for.

The data necessary for the calculation of the lapse rate, the wind speed and the direction were taken from the two daily reports from the radiosonde balloon ascents.[1] The data for the surface wind were used. The lapse rate over the country, l_c, was calculated as follows:

$$l_c = (t_s - t_{900}) / H$$

where:

t_s = the surface temperature

t_{900} = the 900-mb surface temperature

H = the height to the 900-mb surface in m.

These values of the lapse rate were then together with respective wind speed listed in two separate tables, one for the early morning and the other for the afternoons, under the actual wind direction. The corresponding early morning and afternoon mean values were then calculated for each wind direction. These values are listed in Table 18.

B. Emission

The location and emission rate of the pollution sources were

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[1]Canada, Dept. of Transport, Met. Branch, Monthly Bulletin. Canadian Radiosonde Data, Toronto (1961-1964).

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TABLE 18 - CALCULATED AND MEASURED CONCENTRATION OF PARTICULATE MATTER AT CITY HALL, EDMONTON DURING EIGHT WINTER MONTHS 1961 TO 1964

Wind direction	Mean lapse rate °C/100m	Number of observations	Wind speed u, m/s	Max. mixing height h,m	u h m^2/s	Number of sources	Total mass per time and length g/hr,m	Part.matter concentration, $\mu g/m^3$ calculated	Part.matter concentration, $\mu g/m^3$ measured
0500 MST									
N	0.39	24	5.6	492	2756	2	7.94	0.8	6.4
NE	-0.77	15	3.3	170	562	5	49.12	24.3	11.5
E	-1.12	18	2.6	142	362	4	32.64	25.1	15.2
SE	-1.35	19	3.2	128	410	3	107.58	73.7	11.7
S	-2.44	61	2.9	87	253	7	13.28	14.6	13.2
SW	-1.81	34	3.0	107	316	3	10.45	9.2	10.7
W	-1.46	24	2.4	122	518	6	30.22	16.2	9.8
NW	0.02	21	5.9	306	1819	3	57.00	8.7	7.9
Mean	-1.36	27	3.5	174	767	4	30.77	18.6*	11.1
1700 MST									
N	0.20	16	3.6	373	1343	3	7.43	1.5	17.3
NE	-0.30	24	3.9	231	899	13	96.48	29.8	23.2
E	0.60	6	4.5	750	3375	7	156.78	12.9	7.7
SE	-0.74	31	4.2	172	723	4	108.66	41.8	17.2
S	-0.41	47	3.0	213	638	12	83.76	36.5	29.0
SW	-0.64	21	3.2	183	585	5	58.81	28.0	26.0
W	0.22	44	5.0	388	1938	12	89.11	12.8	17.6
NW	-0.48	26	5.3	579	3069	11	290.13	26.3	14.0
Mean	-0.16	27	4.1	353	1357	9	108.74	26.2*	20.7

*This figure is the weighted mean of the calculated concentrations for each wind direction. If the mean is calculated as the weighted mean of the total mass per time unit and length unit divided by the weighted mean of u times h, the mean concentration is: 0500 11.2 $\mu g/m^3$, 1700 22,2 $\mu g/m^3$.

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taken from the source material of the source survey in the city.[2] This report gave the yearly emission of particulate matter for 200 of the largest industries in the city. The number of hours the plants were operating was also given. The hourly emission was then calculated as the total yearly emission divided by the number of hours the plant was operating per year. As the source material was confidential, no tables of the results can be given here.

The following assumptions had to be made:

1. Industries operating nine hours or less per day were not emitting at the period 0400-0600 hours, but were at 1400-1600 hrs.
2. Domestic garbage burned uniformly four hours per day. No emission was assumed in the early morning, average emission in the afternoon. The emission was centered at one spot 2 km from City Hall in each of the eight directions. These assumptions are rather weak, but the total emission from this source is very small.
3. The combustion of oil at the power plant limited to the period December 1 to March 1. The emission was uniformly distributed during this time.
4. Open garbage dumps burning continuously and evenly throughout the year.
5. The emission from the burning of commercial waste and the emission from the traffic distributed both in time and space in the same way.

Location and emission distribution. Since precise locations of the emission sources were necessary in (XII.19) the author chose to

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[2] J.J. Rolston, A Study of Air Pollution Sources and their Significance in Edmonton, Alberta, Govt. of the Province of Alberta, Dept. of Public Health, Div. of Sanitary Engineering, 1964.

confine the total emission from the burning of commercial waste and traffic to a few locations. These were chosen in the following manner: one-tenth of the total emission was centered at the intersection of 82nd Avenue and 104th Street (see Fig. 35). The remaining nine-tenths of the emission were distributed among three centers in the downtown area, one to the west, one to the southwest, and one to the south of City Hall. If the downtown area is divided into sectors according to directions from City Hall (see Fig. 35), the areas of the southern and the western sectors are equal, while the southwestern sector is double the size of the others. The remaining nine-tenths of the emission were therefore divided in four quarters, one centered 300 m south of City Hall, two quarters 500 m southwest of City Hall and the last quarter 500 m west of City Hall. The distances were chosen so that the assumed emitting source was located in the center of each section.

Emission cycle. There is definitely a pronounced daily cycle of the emission from traffic and burning of commercial waste. However, it was impossible to get any exact figures of the emission. In order to avoid the use of arbitrary figures, the results from an earlier investigation were used (see page 113). As pointed out earlier, the number of occurrences of soiling indexes larger than 0.9 for winds from the south and southwest was approximately three times as great for 1400 to 1800 hrs as for the period 0200 to 0600 hrs. Since there are no data available of the diurnal variation of the concentration by wind direction, an assumption that the actual mean concentration was closely related to the number of periods with a soiling index larger than 0.9 was made. Any attempt to use another relationship curve than a linear one between the number of "polluted periods" and the mean concentration would

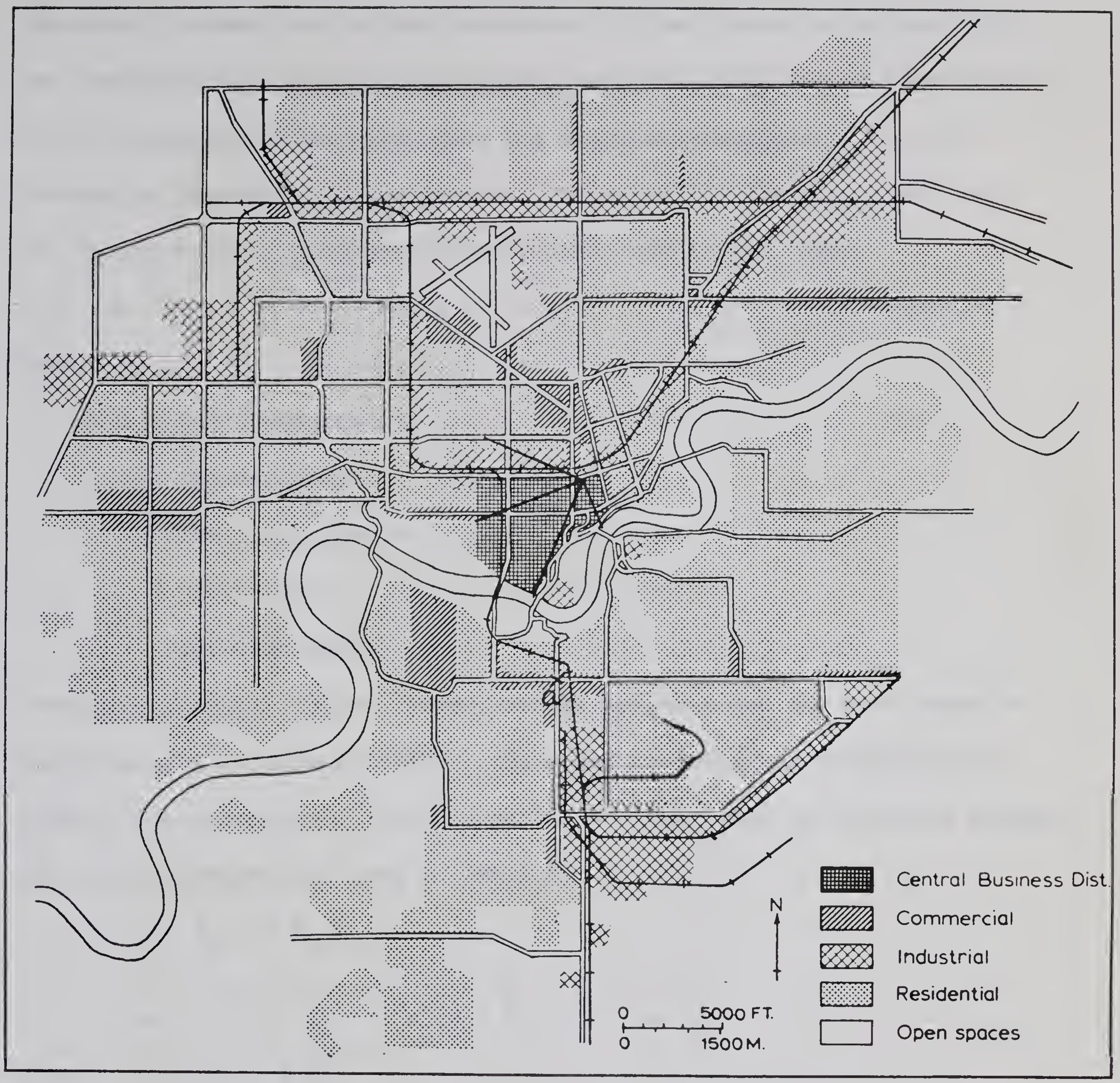

Fig. 35. The downtown area, Edmonton, divided into sectors according to wind directions (S, SW and W) from City Hall

Legend: a = the intersection of 82nd Avenue and 104th St.

introduce too many subjective decisions. It was therefore assumed that the concentration in early morning was also one-third of the late afternoon concentration for winds from the south and southwest. The concentration depends on three factors: the emission, the wind speed and the mixing height. This can be written in simplified form[3]:

$$C = E\,k / h\,v \qquad \text{(XIII.1)}$$

where:

C = the concentration

E = the emission

h = the mixing height

k = a constant

v = the wind speed

According to Table 18 the maximum mixing height times the wind speed in early morning for winds from the south and southwest is about half of that in the afternoon. This connection together with the relation between the concentrations was used in (XIII.1):

$$C_m = E_m\,k / h_m\,v_m$$

$$C_a = 3\,C_m = E_a\,k / h_a\,v_a = E_a\,k / 2\,h_m\,v_m$$

Thus: $E_a = 6\,E_m$

where:

a refers to afternoon values and m early morning ones. For the city the source survey showed that there were no major industries to the south and southwest, so the emission in these two directions can be assumed to be limited to traffic and burning of commercial waste.

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[3]P.W. Summers, "An Urban Heat Island Model, its Role in Air Pollution Problems with Application to Montreal," presented at the First Canadian Conference on Micrometeorology, Toronto, 1965.

Table 17 furthermore indicates that the concentration is half of the average in early morning and one and a half times the average in the afternoon; thus $E_m = 1/3\ E_{av}$ and $E_a = 2\ E_{av}$

where:

E_{av} = the daily average emission.

Both the choice of the locations of the sources and the daily cycles of emission can easily be criticized, but it was felt that it was better to have some kind of actual measurements even if they were somewhat uncertain than to use completely arbitrary figures. The results were also well in agreement with what could be expected. The emission cycle was assumed to be the same for all three directions.

6. The emission is less during the weekend than during the rest of the week. However, no trial to account for this fact was done, as it can be assumed that during the weekends the wind directions were fairly evenly distributed.

7. In the few cases where it was necessary to use the horizontal dispersion coefficient, σ_y , σ_y values for neutral conditions were used (Fig. 31).

With these assumptions, plus the meteorological ones, the concentration at City Hall was calculated for early morning and afternoon for the eight main wind directions. The results from this calculation are shown in Table 18, as well as in graph form in Fig. 36.

C. Discussion of the Results

There is definitely a close relationship between the calculated and the measured values. This is all the more obvious as the concentration of pollutants at City Hall varied more than five times among the wind directions. For two directions, north and southeast, the relationship is less close than for the others. The reason for these

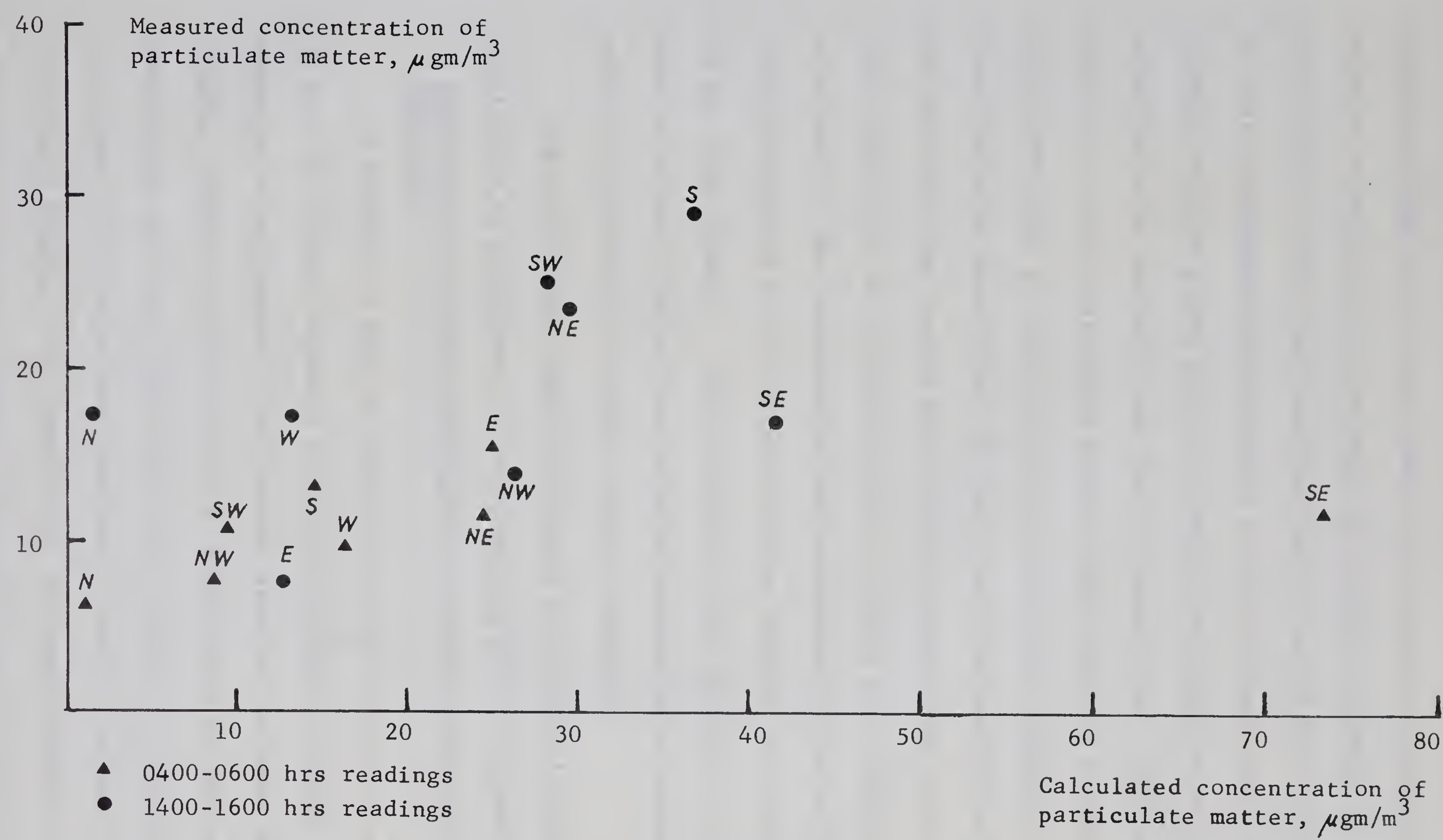

Fig. 36. Calculated and measured concentration of particulate matter in early morning and late afternoon for eight winter months 1961-1964 at City Hall, Edmonton.

deviations seems to be errors made in the emission calculations. The emission in the sector to the north of City Hall according to the source study is about ten times less than it is for any other sector. To obtain the measured concentration at City Hall with north winds, assuming that the source study is correct, the height of the heat island has to be one-tenth less than it actually was. This would give north by far the lowest mixing height, which certainly is unrealistic since north winds are more closely associated with unstable air than those from other directions. The most likely explanation is therefore that there are some sources which are not accounted for in the emission study, especially as the city map (Fig. 1) shows large industrial areas to the north. The concentration with southeasterly wind is almost completely determined by the emission from two sources, the city incinerator and one large industry. Over-estimation of the emission for one of these would easily explain the deviation between the calculated and the measured concentration for winds from the southeast.

The calculations support the theory of a vertically uniform distribution of pollutants over an urban area within the heat island.

D. Extension of the Early Morning and the Afternoon Results to the Whole Day

An attempt was made to extend the values for the two periods to the rest of the day, because a picture of the agents causing the concentration of pollutants in the downtown area for the whole day is valuable. However, since there are no measurements for the vertical stability for the rest of the hours, only estimates of the mixing height can be made. This height has a maximum at about 2 p.m. and a minimum in the early morning. The curve in Fig. 37 seemed therefore to be the most likely one for the quantity: the mixing height times the wind speed.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

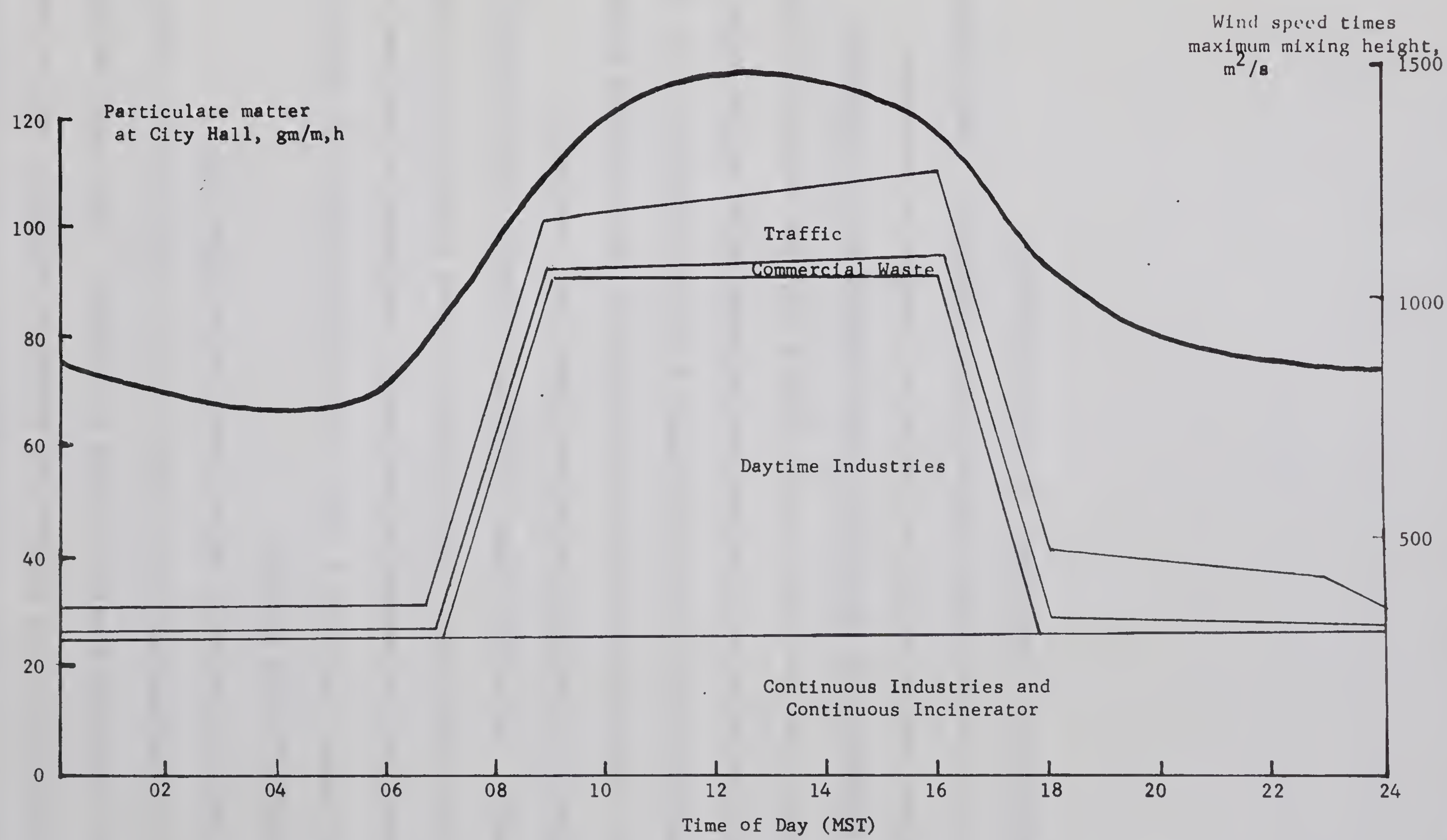

Fig. 37. Estimated mass of particulate matter per hour and meter, and the wind speed times the maximum mixing height by the hour at City Hall, Edmonton.

<u>Legend</u>: The thick curved line is the estimated wind speed times the maximum mixing height with the scale on the right abscissa. The thin straight lines are the estimated amount of particulate matter per hour and meter with the scale on the left abscissa. For example at 0700 hrs the mass at City Hall is about 30 g/hour,m, of this amount 26 g come from continuous operating industries and incinerators, 1 g from the burning of commercial waste and 3 g from the traffic. The windspeed times the maximum mixing height is about 750 m^2/s. This situation gives a low concentration (11.2 g/m^3) which is indicated by a large space between the line for the total amount of pollutants (the upper straight line) and the line for the windspeed times the maximum mixing height (the thick curved line).

As can be seen from equation XII.1 (page 133) the maximum concentration is reached when the ratio between the amount of pollution and the wind speed times the maximum mixing height is greatest. This ratio as given in Fig. 37 has approximately the same diurnal variation as the actual measured daily variation of smoke concentration (Fig. 26).

E. Application of the Results

This study indicates a close relationship between the concentration of pollutants and the maximum mixing height, the height of the heat island created by the city itself. This height has been calculated for eight winter months. The height shows a definite variation with wind direction, being highest with northerly winds and lowest with southerly.

This relationship, together with the fact that southerly winds were predominant during the actual months plus the assumption that the investigated two periods of the day are representative for the whole day (an assumption that can well be made) should rule out any plan to develop polluting industries to the south of the downtown area in Edmonton.

Further studies of the air pollution problem are necessary, especially with regard to the meteorological variables. These studies might beneficially be undertaken as soon as possible.

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